Enhanced micro/nano-tribological performance in partially crystallized 60NiTi film

Wanjuan HE, Qunfeng ZENG*

Key Laboratory of Education Ministry for Modern Design and Rotor-Bearing System, Xi'an Jiaotong University, Xi'an 710049, China

Received: 14 May 2020 / Revised: 23 August 2020 / Accepted: 10 September 2020

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Abstract: The microstructure, mechanical and micro/nano-tribological properties of the 60NiTi film annealed at different temperature were investigated. The results reveal that annealing as-deposited 60NiTi film at 300, 375, and 600 °C for 1 h leads to structural relaxation, partial crystallization and full crystallization, respectively. Compared with the structurally relaxed structure, the partially crystallized structure exhibits increased hardness but decreased elastic modulus. This is because that the elastic modulus is reduced by Voigt model while the hardness is improved by composite effect. Due to the highest hardness and ratio of hardness to elastic modulus (H/E), the partially crystallized 60NiTi film has the lowest penetration depth and residual depth (i.e., groove depth). Besides, the results also reveal that ductile plowing is the dominant wear mechanism for all the annealed 60NiTi films. Under the condition of the ductile plowing, coefficient of friction and wear resistance are related to penetration depth and residual depth, respectively. Therefore, the partially crystallized 60NiTi film shows the best tribological performance at the micro/nano-scale. The current work not only highlights the important roles of hardness and H/E in improving the micro/nano-tribological properties but also concludes an efficient and simple method for simultaneously increasing hardness and H/E .

Keywords: 60NiTi film; partial crystallization; micro/nano-friction; hardness; ratio of hardness to elastic modulus

1 Introduction

With the application of precision mechanical system expanded, the demand for system of high reliability and minimized dimension is growing [1, 2]. This demand has stimulated the research on design and fabrication of micro/nano-electromechanical systems (MEMS/NEMS). The mechanical component of MEMS/NEMS undergoes relative motion at the micro/nano-scale, which can result in friction and wear at the interface [3–8]. These interfacial phenomena are the cause of deterioration and complete failure of MEMS/NEMS [9, 10]. Therefore, decreasing the friction and wear at the interface is essential. However, the application of liquid lubricant to MEMS/NEMS is limited due to its relatively high viscosity. Besides,

solid lubricant is also inappropriate for improving the tribological performance of MEMS/NEMS because solid lubricant can hardly be maintained and repaired after it is worn out during operation. Hence, it is necessary to develop an alternative, such as protective film, to effectively protect the mechanical component from premature wear and excessive friction.

Materials for high tribological performance require high hardness (for mitigating the effects of ploughing and tearing), excellent corrosion resistance (for rendering corrosion resistance) and low density (for reducing centrifugal stress) [11]. But, in terms of the hardness, solely pursuing ultra-hard material is not the optimal approach to enhance the tribological performance [12]. This is because that hard material can result in high friction if the asperities on contacting surfaces interlock

* Corresponding author: Qunfeng ZENG, E-mail: zengqf1949@gmail.com

during sliding [13]. Therefore, an ideal material should have sufficiently high hardness to provide abrasion resistance and sufficiently low elastic modulus to widely distribute applied load [12, 14–16]. It means that the material with high ratio of hardness to elastic modulus (H/E) is desirable. However, increasing H/E is a very difficult task because high hardness is always accompanied with high elastic modulus. In recent years, several new materials with special structures to address this problem have been designed. Yang et al. [16] achieved the favorable variation (i.e., increase in hardness and decrease in elastic modulus) by introducing a special structure with ultrafine ceramic grains embedded into a metallic glass matrix. Penkov et al. [13] found that elastic modulus was reduced while hardness remained nearly unchanged by decreasing the cobalt thickness of a new functional coatings comprising periodically stacked nanolayers of amorphous carbon and cobalt. However, the aforementioned methods to increase H/E rely on the elaborate experimental designs. Therefore, increasing H/E , especially by simple method, is still challenging.

Highly Ni-rich NiTi alloys (>52 at%) have an advantageous set of properties needed for structural application [17]. Among the highly Ni-rich NiTi alloys, one that has recently received wide interest is 60NiTi (60 wt% Ni) bulk alloy [17–28]. Neupane et al. [28] found that 60NiTi bulk alloy exhibited excellent tribological performance under dry reciprocating movement, and its high H/E was an important contributor. However, in terms of 60NiTi film, only few studies exist, and they mainly focus on the effects of annealing on hardness and corrosion resistance of sputter-deposited 60NiTi film [29]. In another word, the tribological performance of 60NiTi film remains unexplored. In this work, we prepared 60NiTi film by magnetron sputtering. Then, the as-deposited 60NiTi film was annealed at different temperature. The micro/nano-tribological performance of 60NiTi film at different crystallization stage was systematically investigated. This paper aims to evaluate the potential of 60NiTi film as the protective film at the micro/nano-scale.

2 Materials and experimental procedures

60NiTi films were grown on silicon (100) wafers by

magnetron sputtering using 60NiTi target with a size of $\phi 76.2$ mm $\times$ 5 mm and a purity of 99.99%. Prior to film deposition, Si substrates need to be carefully cleaned. The concrete cleaning steps of Si substrates referred to Ref. [30]. The as-deposited films were annealed in a vacuum atmosphere of 5×10^{-4} Pa at 300, 375, and 600 °C for 1 h, followed by furnace cooling. The morphology of the 60NiTi film was investigated using scanning electron microscope (SEM, FEI Quanta FEG). The microstructure of the 60NiTi film was studied with grazing incident diffraction (GID, Bruker D8 ADVANCE). A low grazing angle of X-ray incidence was set at 1°, and detector was scanned at 5 °/min. The fine structures of 60NiTi films were identified using transmission electron microscopy (TEM, JEOL JEM-F200). TEM samples were prepared using a technique outlined by Weaver [31].

Nanoindentation tests were performed on 60NiTi films in displacement-controlled mode using Hysitron Ti950 Triboindenter with a Berkovich diamond pyramid indenter. Loading was carried out at a constant penetration rate of 2 nm/s. The maximum indentation depth was less than 10% of film thickness to guarantee the intrinsic properties of 60NiTi films. When the maximum indentation depth was reached, the indenter was held for 2 s. Subsequently, the indenter was unloaded at the rate of 2 nm/s. To ensure the repeatability of the experimental data, at least three nanoindentation tests were performed for each experimental condition.

Nano-tribological experiments were carried out on 60NiTi films using Hysitron Ti950 Triboindenter with a 2D transducer to measure their coefficient of friction (COF) and wear resistance at the nano-scale. The conic diamond tip with a radius of 1 μ m and a conical apex angle of $\pi/3$ was used. The scratch length and scratch speed were 10 μ m and 1 μ m/s, respectively. The different normal loads (1 and 3 mN) were employed. Then, the surface morphology of wear scar was investigated using scanning probe microscopy (SPM). Micro-tribological experiments (CSM Instruments) were performed on 60NiTi films to determine their wear resistance at the micro-scale. A spherical diamond indenter with a radius of 100 μ m was used as the counterface material. The scratch length, scratch speed and normal load were 200 μ m, 10 μ m/s, and 100 mN,

respectively. Subsequently, the surface morphology of wear scar was studied using atomic force microscope (AFM, Bruker INNOVA) under tapping mode and optical microscope (OM, OLYMPUS).

3 Results and discussion

3.1 Microstructures of 60NiTi films

It has been reported that annealing at more than 400 °C can fully crystallize as-deposited 60NiTi film, which is still amorphous after annealing at 300 °C [29]. Figures 1(a–c) show the SEM images of the cross-sectional topographies of the 60NiTi films in different heat-treated conditions. It can be seen that increasing annealing temperature can gradually induce the bumps on the sections of the films. From this perspective, the 60NiTi film annealed at 375 °C is supposed to be in a transition state between amorphous structure and fully crystallized structure. As seen in Fig. 1(d), the GID profile of the 60NiTi film annealed at 375 °C reveals the presence of both the broad hump indicated by green line and the sharp diffraction peak. The former stands for the appearance of amorphous phase, while the latter corresponds to cubic NiTi B2 phase (PDF: No. 18-0899). Therefore, the 60NiTi film annealed at 375 °C has partially crystallized structure. By contrast,

the GID profile of the 60NiTi film annealed at 300 °C has only one broad hump, indicating its amorphous structure. And, the GID profile of the 60NiTi film annealed at 600 °C has only sharp diffraction peaks, indicating its fully crystallized structure. The high resolution TEM (HRTEM) image of the annealed 60NiTi film further proves the corresponding structure. As seen in Fig. 1(e), the HRTEM image of the 60NiTi film annealed at 300 °C reveals the typical maze-like contrast inherent to amorphous structure, and no recognizable fringe contrast is observed. In addition to the amorphous zone, the HRTEM image (Fig. 1(f)) of the 60NiTi film annealed at 375 °C also shows the obvious fringe contrast, indicating the crystalline phase. According to the calculated lattice space, the crystal plane belongs to (001) plane of NiTi B2 phase. With the annealing temperature increased to 600 °C, no amorphous zone is found in the HRTEM image (Fig. 1(g)).

3.2 Mechanical properties

To study the effect of annealing at different temperature on mechanical properties, nanoindentation with constant maximum indentation depth (50 nm) was conducted for evaluating the hardness and elastic modulus of each the annealed 60NiTi film. As-deposited 60NiTi film was tested as a control.

Fig. 1 (a–c) Cross-sectional images and (d) GID profiles of all the annealed 60NiTi films. (e) HRTEM image of film annealed at (e) 300 °C, (f) 375 °C, and (g) 600 °C.

Figures 2(a–d) present representative load-depth curve of each the 60NiTi film. With the increase in annealing temperature, the maximum load is initially increased and then decreased, and reaches its peak at an annealing temperature of 375 °C. The hardness was calculated using the method proposed by Oliver and Pharr [32], and shown in Fig. 2(e). Meanwhile, Fig. 2(e) provides the elastic modulus's result which was calculated based on the slope at the initial unloading segment. It should be mentioned that, although both the as-deposited 60NiTi film (Fig. S1(a) in Electronic Supplementary Material (ESM)) and the 60NiTi film annealed at 300 °C are amorphous, the as-deposited 60NiTi film (Fig. S1(b) in ESM) has larger film thickness than the 60NiTi film annealed at 300 °C, and hardness and elastic modulus of the as-deposited 60NiTi film is lower than those of the 60NiTi film annealed at 300 °C (Fig. 2(e)). The two differences between the as-deposited 60NiTi film and the 60NiTi film annealed at 300 °C can be explained by structural relaxation. It has been reported that annealing as-prepared amorphous material at a relatively low temperature can generate the structurally relaxed but still amorphous structure [33, 34]. The structural relaxation leads to the short-range ordering,

the annihilation of a large population of defects (such as point defects formed during deposition process) and the shrinkage of material volume [35, 36]. These structural changes during the structural relaxation contribute to the increase in mechanical properties [37–39]. Therefore, the 60NiTi film annealed at 300 °C is structurally relaxed. When annealing temperature increased to 375 °C, the hardness continues to improve, while the elastic modulus is reduced. Therefore, as seen in Fig. 2(e), the increased H/E is successfully realized by annealing the as-deposited amorphous 60NiTi film at 375 °C for 1 h. According to aforementioned analysis, the film annealed at 375 °C for 1 h is partially crystallized. Huang et al. [40] found that the partial crystallization of NiTi film after its structural relaxation can reduce elastic modulus. This is because the NiTi B2 ordered phase has lower elastic modulus than its amorphous counterpart, and that the elastic modulus of the generated amorphous/crystalline composite follows Voigt model based on the rule of mixtures [41]. Notably, the theoretical hardness [42] of the NiTi B2 ordered phase is lower than the hardness of the amorphous structure (film annealed at 300 °C). Despite the fact that the crystalline

Fig. 2 (a) Representative load–depth curves of as-deposited 60NiTi film, (b–d) film annealed at 300, 375, and 600 °C. P_{max} is the maximum load, h_r and h_{max} are the residual indentation depth and the maximum indentation depth, respectively. (e) Hardness and elastic modulus of 60NiTi film and (f) recovery ratio of 60NiTi film.

phase has lower hardness than the homogeneously amorphous structure, the occurrence of crystalline phase in the amorphous matrix activates composite effect and improves hardness [43]. This can explain the increase in the hardness of the film annealed at 375 °C. Wolff et al. [44] also reported that the partial crystallization of amorphous $\text{Mg}_{60}\text{Cu}_{30}\text{Y}_{10}$ alloy significantly enhances hardness. In conclusion, compared with the structurally relaxed but still amorphous structure, the partially crystallized structure exhibits increased H/E . Specifically speaking, the elastic modulus is reduced by Voigt model while the hardness is improved by composite effect. With the annealing temperature further increased to 600 °C, both the hardness and elastic modulus fall below those of the film annealed at 300 °C. This is related to the fact that the film annealed at 600 °C contains the NiTi B2 ordered phase with inferior hardness and elastic modulus.

In addition to high H/E , large recoverable strain is also reported as an important contributor to the improved tribological performance [16, 28, 45]. This is because that large recoverable strain is able to make the deformation spring back into its original state as much as possible when removing external stress. The recovery ratio, which is calculated by $(1-h_r/h_{\max})$, can describe the recovery capability and is presented in Fig. 2(f). Although Berkovich indenter employed in this work cannot precisely determine recoverable strain because it causes permanently deformed region beneath the indenter even at elastic deformation stage [46], it is reasonable and feasible to qualitatively describe the relative change in recoverable strain, as done in previous studies [47, 48]. Notably, the film annealed at 300 °C has the higher recovery ratio than the as-deposited amorphous film. This indicates that, although both as-deposited structure and structurally relaxed structure are amorphous, only the structurally relaxed structure can make the most of the inherent high elasticity (~2% recoverable strain [49]) of amorphous structure. The same result was reported in Ref. [37] showing that the structurally relaxed but still amorphous NiTi film has superior recovery capability to the as-deposited amorphous film. With the annealing temperature increased to 375 °C, the recovery ratio is increased, demonstrating

that the partial crystallization of 60NiTi film favors the recovery capability. This is because the superelasticity (~5% recoverable strain [50]) of NiTi B2 ordered phase is larger than the high elasticity of amorphous structure. Such the recovery capability enhancement attributed to the occurrence of crystalline phase is actually based on the synergy effect of the superelasticity from NiTi B2 ordered phase and the high elasticity from amorphous structure [41, 51]. When the film is fully crystallized, the growth trend of recovery ratio is continued. It should be noted that the recovery ratios of the 60NiTi films are measured with the constant maximum indentation depth (50 nm).

3.3 Micro-tribological properties

The optical microscope images of the wear scars of the annealed 60NiTi films are shown in Fig. 3(a). It can be seen that the wear scar of each annealed 60NiTi film exhibits relatively smooth groove without microcrack nor fractured debris, indicating the ductile plowing wear mechanism. Intuitively, the groove of the film annealed at 375 °C was shallowest while that of the film annealed at 600 °C was deepest. Such observed groove depth is actually the residual depth (R_d). The residual depth is illustrated in Fig. 3(b). When the spherical diamond indenter slides against the annealed 60NiTi film, the contacting surface of the annealed 60NiTi film is subjected to deformation, the corresponding depth is the penetration depth (P_d). The deformed surface springs back to some extent with the residual depth left when the indenter slides away.

Figure 3(c) presents the profiles of penetration depth and residual depth vs scratch distance. The penetration depth is associated with its normal load (positive correlation) and hardness (negative correlation) [52]. For a given normal load, a higher hardness yields a lower penetration depth. Therefore, as seen from the whole wear scar, the penetration depth of the film annealed at 375 °C is lowest, while that of the film annealed at 600 °C reaches its highest value. In terms of the residual depth, it depends on the penetration depth and the recovery index which is calculated by $(1-R_d/P_d)$. The profile of recovery index vs scratch distance for each annealed 60NiTi film is shown in Fig. 3(d). As seen from the whole wear scar, the film

Fig. 3 (a) OM images of the wear scars of all the annealed 60NiTi films, (b) schematic of residual depth and penetration depth, (c) profiles of penetration depth and residual depth vs scratch distance for each the annealed 60NiTi films, (d) profile of recovery index vs scratch distance for each the annealed 60NiTi film, and (e) plot of wear rate, dimensionless parameter, and cross-section profile for each annealed 60NiTi film.

annealed at 375 °C almost always has the maximum recovery index, while the film annealed at 600 °C exhibits the minimum recovery index. Therefore, both the penetration depth and the recovery index minimize the residual depth of the film annealed at 375 °C while maximize that of the film annealed at 600 °C.

Although the changing trend of the residual depth with the annealing temperature is the same with that of the penetration depth, there is no direct correlation between the penetration depth and the residual depth. This is because the penetration depth is related to the hardness, while the residual depth is connected with the penetration depth and the recovery index. In fact, the recovery index is the reflection of the plasticity index, and the plasticity index can be evaluated by H/E [53]. A higher H/E allows a larger elastic strain prior to plastic deformation [54, 55]. In another word,

the recovery index, H/E and the plasticity index essentially contain the same information [56]. It should be mentioned that, although both the recovery ratio in Fig. 2(f) and the recovery ratio index in Fig. 3(d) can describe the extent of springback after the retraction of the indenter, their changing trends with the annealing temperature are different. This is because that the recovery ratio is measured with the constant maximum indentation depth, while the recovery index is determined with the constant load. The full crystallization of the film annealed at 600 °C improves its recovery ratio under the same maximum indentation depth. However, the decreased H/E makes the film annealed at 600 °C undergo the increased plastic deformation under the same load, resulting in the declined recovery index.

To evaluate the wear resistance, we calculate the

equivalent volumetric specific wear rate using the expression $K \left[\frac{\text{mm}^3}{\text{N} \cdot \text{mm}} \right] = \frac{A \cdot L}{F_N \cdot N \cdot L}$, where A , L , F_N and N respectively denote cross-section area of wear scar, scratch length, normal load and total sliding passes. As seen in Fig. 3(c), the residual depth varies slightly with the scratch distance for each the annealed 60NiTi film. This indicates that the cross-section area obtained through the integration of cross-section profile varies slightly with the position of cross-section profile. However, such difference in the cross-section area does not influence the relative change of the wear resistance. As indicated in Figs. 3(a, b), the position with about 25 μm away from the starting point of wear scar is selected as a representative. According to the AFM image (Fig. S2 in ESM) of wear scar, the cross-section profile of each the annealed 60NiTi film is provided as inset in Fig. 3(e). The wear rates of all the annealed 60NiTi films are presented and compared in Fig. 3(e). The wear rate of the film annealed at 375 °C reaches an order of magnitude of 10^{-7} , while those of the films annealed at 300 and 600 °C have the same order of magnitude of 10^{-6} . The wear resistance can be also described by the dimensionless parameter K' in Archard's equation using the expression $K' = \frac{V_w \cdot H}{F_N \cdot L}$, where V_w , H , F_N , and L respectively denote wear volume, hardness, normal load, and scratch length [57, 58]. As with the result of the wear rate, the dimensionless parameter of the film annealed at 375 °C is approximately one order of magnitude less than those of the other annealed 60NiTi films (Fig. 3(e)). These two results indicate that the partially crystallized film exhibits the relatively excellent wear resistance at the micro-scale.

3.4 Nano-tribological properties

According to the scratch process (Fig. S3 in ESM), all the annealed 60NiTi films were scratched for a period of 10 s. The scanning probe microscopy image of the corresponding wear scar is shown in Fig. 4(a). It can be seen that all the wear scars share one common characteristic, i.e., materials pile up along the groove edges. This indicates that the ductile plowing is the dominant wear mechanism for all the annealed 60NiTi films [59–61]. The profile of COF vs scratch time for

the normal load of 1 mN is shown in Fig. 4(b). It is readily seen that each the COF profile consists of two distinct regions, i.e. the initial unstable region where the COF is rapidly increased because the tip is trying to settle down and the subsequent steady-state region where the COF is nearly constant. This is exactly similar to the results reported in other tribology studies [61, 62]. In terms of the steady-state region, the COF profile varies in its height with the annealing temperature. The film annealed at 600 °C shows the highest COF profile, while the film annealed at 375 °C has the lowest COF profile. Each the COF profile contains many serration, i.e. the so-called stick-slip behavior [61, 63–65]. As there is no localized fracture or debris on the scratched surface, the stick-slip behavior actually reflects the intermittent surface deformation. The scratch process during the period ranging from 12.5 to 21 s is chosen as a typical steady-state region. Based on this, the average COF is obtained and indicated by the inset in Fig. 4(b). Clearly, the partially crystallized film has the minimum average COF.

The cross-section profile of wear scar is indicated by the inset in Fig. 4(c). Clearly, the partially crystallized film has the shallowest groove and almost invisible pile-up. By carefully examining the cross-section profile of the film annealed at 300 or 600 °C, it is found that the pile-up along the two sides of wear scar is not exactly symmetrical. This is probably due to the misalignment between the film surface and the tip [66]. Based on the cross-section profile of each the annealed 60NiTi film, the wear rate and the dimensionless parameter are calculated. As seen in Fig. 4(c), the partially crystallized film has relatively excellent wear resistance at the nano-scale.

With the normal load increased to 3 mN, as seen in Fig. 4(d), each COF profile at the steady-state region is higher. Therefore, as indicated by the inset in Fig. 4(d), the average COF of each annealed 60NiTi film is increased. Meanwhile, as indicated by the inset in Fig. 4(e), the enhanced load can significantly increase the pile-up height and the groove depth. However, as seen in Fig. 4(e), the wear rate and the dimensionless parameter of each annealed 60NiTi film were decreased. Moreover, the partially crystallized film still presents the minimum average COF and the

Fig. 4 (a) SPM images of the wear scars of all the annealed 60NiTi films. Profiles of COF vs scratch time for each the annealed 60NiTi film in the case of (b) 1 and (d) 3 mN. Plots of wear rate, dimensionless parameter, and cross-section profile of each the annealed 60NiTi film in the case of (c) 1 and (e) 3 mN.

relatively excellent wear resistance. And, the cross-section profile of each the annealed 60NiTi film reveals that the pile-up along the two sides of wear scar is basically symmetrical. This suggests that the enhanced load can keep the good contact of the film

surface and the tip during sliding.

3.5 Friction and wear reduction mechanism

According to the Bowden-Tabor's model [67], the COF (μ) can be expressed as $\mu = \mu_a + \mu_p$, where μ_a is the

adhesion friction coefficient and μ_p is the plowing friction coefficient. In terms of the adhesion force, the mutual solid solubility of two contacting bodies can evaluate their tendency of adhesion. The higher mutual solid solubility of two contacting bodies causes the larger adhesion force, leading to the higher adhesion friction coefficient. In this work, the tip is composed of diamond, which is chemically inert and is not expected to adhere to the metallic surface [68]. Therefore, the adhesion between the film material and the tip is small. In addition, the pile-up (Fig. 4(a)) also confirms that the dominant wear mechanism is the plowing rather than the adhesion. Therefore, the change of the average COF with annealing temperature and normal load is primarily determined by μ_p . Notably, μ_p is positively correlated with P_d [52]. This is because that the higher penetration depth results in the bigger contact area between the film material and the submerged part of the tip, leading to the stronger obstacle against sliding.

The nano-tribological experiment conducted in this work does not record the penetration depth, but according to the micro-tribological experiment, the higher hardness yields the lower penetration depth. Therefore, it is reasonable to believe that the film annealed at 375 °C has the lowest penetration depth under the nano-tribological experimental condition. This is the reason why the film annealed at 375 °C has the minimum average COF in both the cases of 1 and 3 mN. Meanwhile, due to the highest hardness and H/E , the film annealed at 375 °C is of the lowest residual depth (i.e., groove depth) in both the cases of 1 and 3 mN. Therefore, as with the micro-tribological experiment, the nano-tribological experiment also reveals that the film annealed at 375 °C shows the most excellent wear resistance.

Although the average COF and wear resistance of the partially crystallized film are not the best compared with the result in open literature [69], this work concludes an effective and simple method for increasing the hardness and especially H/E , i.e., embedding the crystalline phase into its amorphous counterpart to reduce the elastic modulus by Voigt model while increase the hardness by composite effect. In addition, introducing the second phase, such as nitride phase, that has higher hardness and elastic modulus than

the matrix phase can also increase the hardness and H/E [16]. This is because that, although such the second phase can increase both hardness and elastic modulus, the increase in hardness is more significant than the increase in elastic modulus. The two cases are illustrated in Fig. 5. When the conic diamond tip slides against the annealed 60NiTi film, the penetration depth that determines the plowing friction coefficient depends on the hardness. The residual depth that reflects the wear resistance relies on both the hardness and H/E . However, not all the composite can increase the hardness and H/E [70]. Therefore, only the appropriate composite has the improved tribological performance.

4 Conclusions

The microstructures, mechanical and micro/nano-tribological properties of the 60NiTi films annealed at different temperatures were investigated. The results were used to evaluate the potential of 60NiTi film as a protective film at the micro/nano-scale. The main findings in this work were summarized as follows:

- 1) Because elastic modulus is reduced by Voigt model while hardness is improved by composite effect, partially crystallized 60NiTi film has the highest hardness and H/E among structurally relaxed, partially crystallized and fully crystallized 60NiTi films.
- 2) High hardness leads to low penetration depth, and high H/E allows large elastic strain prior to plastic deformation. The partially crystallized 60NiTi film has the lowest penetration depth and residual depth due to its highest hardness and H/E .

Fig. 5 Schematic of increasing the hardness and H/E by forming the composite to improve the tribological performance.

3) The ductile plowing is the dominant wear mechanism for all the annealed 60NiTi films. Under the condition of the ductile plowing, coefficient of friction and wear resistance are related to penetration depth and residual depth, respectively.

Acknowledgements

The present work was financially supported by the Fundamental Research Funds for the Central Universities (xzy022019015) and the National Natural Science Foundation of China (51675409).

Electronic Supplementary Material: Supplementary material is available in the online version of this article at <https://doi.org/10.1007/s40544-020-0451-7>.

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Qunfeng ZENG. He is an associate professor at the School of Mechanical Engineering, Xi'an Jiaotong University, China. He lectures on mechanical engineering, and is dedicated in

research on coatings for mechanical engineering applications. His main research is on sealing, wear, lubrication and corrosion mechanisms, and control methods of NiTi alloys, steels, DLC films, and other anti-corrosion and lubricating materials.

Wanjun HE. He received his master degree in materials science in 2018 from Northwestern Polytechnical University. He has been a Ph.D.

student of the School of Mechanical Engineering at Xi'an Jiaotong University since 2018. His main research is on antifriction and wear resistance of thin film.