Development of TiNi Alloy Superelastic Guidewire Needle for New Type of Medical Arthroscopic Surgery

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Abstract. This research focuses on the development of TiNi alloy super elastic guide needles for new medical arthroscopic surgery. With the development of sports medicine and the increasing demand for minimally invasive arthroscopic surgeries, the limitations of traditional surgical needles have become more prominent. TiNi shape - memory alloy (SMA) has unique super elasticity, shape - memory effect, and excellent mechanical properties, making it suitable for manufacturing super elastic suture needles. The project aimed to develop high - performance nickel - rich Ti - 50.8Ni - 0.4V SMA. The preparation process included designing alloys, melting into ingots, hot forging, rolling, and heat treatment. Various experimental methods were used, such as SEM, OM, DSC, TEM, and tensile testing, to analyze the phase transformation temperature, phase composition, microstructure, and super elastic properties of the alloys under different processing conditions. The results showed that for NiTi alloy wires, when annealed at 400 - 600 °C, as the heat - treatment temperature increased, the critical stress for stress - induced martensitic transformation decreased, the residual strain after tensile testing increased, and the super elasticity decreased significantly. When aged at 500 °C, with the prolongation of aging time, similar changes occurred. In the cyclic stress - strain curves, as the heat - treatment temperature increased, the residual strain of the wire increased, indicating a greater loss of super elasticity. However, wires annealed at 400 - 450 °C showed good continuous super elasticity. Also, the fatigue performance test of the alloy showed a fatigue life of more than 88,800 cycles under a stress of 200 MPa, with low energy loss and little impact on accuracy during use. In conclusion, low - temperature and short - time heat treatment is beneficial for obtaining good superelasticity of the alloy. The research provides a theoretical basis and experimental support for the actual production and application of superelastic guide needles with high strength and superelasticity for low - temperature use in arthroscopic surgeries.

Keywords: TiNi alloy; Superelastic guide needle; Heat treatment; Phase transformation; Mechanical properties.

1. Research Background

Sports medicine is an emerging discipline and is currently one of the most vigorously developing disciplines. With the improvement of people's living standards and health awareness, the number of people engaging in physical fitness has increased significantly. Consequently, the number of sports injury patients has also risen, leading to a rapid increase in surgical demands. The development of minimally invasive, endoscopic, and robotic surgeries has brought great benefits to patients, such as less surgical trauma and faster recovery. However, it also poses higher requirements for doctors' technical capabilities. Most surgeries in this discipline rely on arthroscopes, but the learning curve for endoscopic techniques is very long. Among them, the most difficult part is the endoscopic suture technique, which is also the most basic and commonly used technique, involving the suturing of ligaments, tendons, and even bones. The operating space of an arthroscope is much smaller than that of a laparoscope, with limited vision and a narrow operating space, making the operation difficult and requiring a high level of technical proficiency from the operator. In addition, the currently used needles are of fixed size and curvature and cannot be bent or deformed. Since the injury conditions of different patients vary, surgical needles of the same shape and size are not suitable for all patients. Moreover, the surgical needles should be adjusted according to different affected areas. These limitations make endoscopic suturing extremely difficult. It is often the case that "you can see the target but can't suture it, which is extremely frustrating." Sometimes, it takes a long time and a great deal of effort to suture a single stitch properly, which greatly restricts the development and progress of minimally invasive endoscopic surgeries. For patients, this will prolong the expected surgical time and increase the surgical risk. In mild cases, ineffective suturing may lead to various iatrogenic injuries or secondary displacement due to insecure fixation. In severe cases, the needle may break and remain in the body, or forced bending may cause tissue damage, and in the worst - case scenario, it may even cause disability or death to the patient. How to suture effectively, reduce the difficulty of suturing, improve the suturing efficiency, and make the surgical needles adaptable to different patients according to the actual situation has always been a problem we are committed to solving. Therefore, it is necessary to improve the performance and mechanical strength of surgical needles so that patients can receive prompt treatment during surgery and avoid secondary injuries. Titanium - nickel shape - memory alloy has become a choice to meet the above requirements as a material for surgical needles.

Shape - memory alloys have been widely used in various fields of industry, medicine, and daily life due to their unique superelasticity, shape - memory effect, and excellent mechanical properties. Especially in the medical field, with the continuous in - depth research in this area. As the most representative shape - memory alloy, near - equiatomic NiTi alloy has become a new high - end functional material in the fields of electronics, medicine, and daily necessities due to its unique properties. In particular, nickel - rich NiTi alloys with a Ni content greater than 50.5 at. % have more excellent comprehensive properties. Currently, 90% of the medical applications of NiTi alloy products utilize its superelasticity.

TiNi shape - memory alloy (shape memory alloys, abbreviated as SMA) is an intelligent material with a shape - memory effect (shape memory effects, abbreviated as SME). NiTi alloy can exhibit good superelasticity after appropriate treatment. Superelasticity refers to the phenomenon that the strain generated by a specimen under external force is much larger than the elastic - limit strain of general materials and can automatically recover when the load is removed. The shape - memory effect is one of the basic characteristics of TiNi memory alloys. The formation of SME is closely related to thermoelastic martensitic transformation. Alloy materials with thermoelastic martensitic transformation have a complete shape - memory effect. TiNi - based shape - memory alloys are in the martensite phase with a B19 structure at low temperatures, denoted as the M phase; and in the parent phase with a B2 structure at high temperatures, that is, the austenite phase, denoted as the A phase. Thermoelastic martensitic transformation is closely related to temperature changes. It is mainly determined by four characteristic temperature points that determine the transformation process, including the as point (the starting temperature of martensite reverse transformation), the Af point (the ending temperature of martensite reverse transformation), the Ms point (the starting temperature of martensite transformation), and the Mf point (the ending temperature of martensite transformation). The parent phase A of TiNi alloy has a highly symmetric crystal structure, while the low - temperature M phase has a lower symmetry. The difference in crystal - structure symmetry makes multiple martensite variants form within one grain of the A phase during the temperature - decreasing process. These martensite variants have different orientations, and this process is called the martensitic transformation of the alloy. When a certain stress is applied to the alloy at this time, the M variants will undergo re - orientation, and the variants with different orientations will eventually transform into an M variant with a consistent orientation. The strain generated by the transformation accumulates along the stress - loading direction, causing the macroscopic shape of the alloy to change. After the external force is removed, the shape of the alloy does not change. As the temperature rises to as, the alloy begins to undergo martensite reverse transformation. When the temperature rises to Af, the martensite reverse transformation ends, and the alloy structure is completely composed of A, and the macroscopic shape returns to the state before deformation, that is, the alloy exhibits the shape - memory effect. The thermoelastic martensitic transformation process refers to the process in which thermoelastic martensite forms, changes its orientation, and disappears under certain temperature and external stress. A specimen in the parent - phase state can induce martensitic transformation under unidirectional stress. The martensite variant in the most favorable phase relative to the stress will be preferentially generated in the alloy. At this time, the overall alloy will show macroscopic shape changes. However, this martensite can only be stable under stress. Once the stress is removed, an inverse transformation will immediately occur, returning to the parent - phase state, and the macroscopic deformation generated under external stress will also completely disappear with the occurrence of the inverse transformation. This is the mechanism of transformation superelasticity.

SMA has a wide range of applications in engineering. Currently, it has expanded to many fields such as biomedicine, aerospace, robotics, and the automotive industry. In the biomedical field, the superelasticity of TiNi alloy can be used to ensure that orthopedic structures provide long - term corrective forces. In dentistry, TiNi alloy wires are used to make dental orthodontic wires to correct abnormally growing teeth. In orthopedics, TiNi alloy rods are used to make spinal orthosis to correct deformed spines.

In the aerospace field, shape - memory alloys can be used to drive the movement of specific structures to change the structural characteristics or trigger preset actions. The United States' SAMPSON used SMA bundle drivers and intelligent structures implanted with SMA wires to achieve the pitch adjustment of the inlet cowl and the leading edge of the F - 18 fighter and the shape adjustment of the inner wall of the flow channel, effectively reducing flight fuel consumption and increasing the combat radius of the fighter.

In the robotics field, SMA can be used as a driver to simulate biological muscles and drive robots to achieve specific actions. The University of Tokyo in Japan used SMA wires to drive the movement of a manipulator to imitate human grasping actions. Virginia Tech in the United States embedded multiple SMA wires in the elastic material of a robot's face and used a special control strategy to drive the movement of the robot's face to imitate human facial expressions.

In the automotive industry, SMA can be used as a driver or sensor to drive the structure of a car or sense the operating state of the car and respond to achieve specific functions. The SMA temperature - adaptive fuel feeder uses the adaptive changes of SMA springs under high and low temperatures to adjust the fuel volume. When the outside temperature drops, causing the viscosity of the fuel to increase and the flow to slow down, the spring elongates, the fuel supply port enlarges, and the fuel supply automatically increases; when the temperature is high, the fuel volume automatically decreases, ensuring a stable fuel supply.

NASA in the United States has carried out systematic research on TiNi memory alloys. The research content includes uniaxial tension, bending, and torsional stress - strain response, and heating - recovery mechanical behavior. Cyclic loading will affect the shape - memory effect of SMA. Urbina et al. studied the influence of cyclic loading on the performance stability of TiNi materials at different environmental temperatures. The results show that the environmental temperature will affect the plastic strain, maximum transformation strain, transformation temperature, etc. of TiNi materials during the cyclic process. Atli et al. studied the attenuation mechanical behavior of different TiNi - based memory alloys under different stress cycles.

Different heat - treatment methods will affect the mechanical properties of SMA. The research results of Cesari et al. show that different annealing temperatures will affect the microstructure of high - temperature SMA, thus causing changes in macroscopic mechanical properties. Miyazaki et al. studied the influence of annealing at different temperatures after cold working of TiNi memory alloys on the phase - transformation critical stress of the materials. Sadiq et al.'s research results show that the annealing temperature also affects the maximum recovery stress of SMA materials; when the annealing temperature is lower than 600 °C, the maximum recovery stress will drop sharply.

Many scholars have carried out a large amount of research work to establish constitutive models to describe the influence law of temperature on the stress - strain relationship of SMA. Landau established the free - energy expression of SMA based on the microscopic thermo dynamics theory and according to the free - energy composition of the material, and established the SMA constitutive model by taking the partial derivative of the free energy. Sun and Wang used the self - consistent method proposed by Mori - Tanaka and combined with the crystallographic phenomenological theory to deduce the interaction - energy expression during the martensite transformation process, obtained the function expression of the residual free energy per unit volume of a single crystal, and promoted the development of the meso - mechanical SMA constitutive model of the shape - memory effect and superelasticity.

TiNi shape - memory alloy has the characteristics of high strength, low Young's modulus, and superelasticity, which is very suitable for use as a material for superelastic suture needles. Through appropriate cold rolling and heat - treatment processes, TiNi alloys with high hardness, superelasticity, and high plastic toughness can be obtained for the preparation of superelastic suture needles that can be bent arbitrarily. It has the following advantages:

(1) Excellent superelasticity, which can spontaneously and uniformly expand to the required size, solving the problem of secondary displacement during the suturing process.

(2) Small in size, so it can be used in arthroscopic surgeries in a narrow operating space.

(3) Superior fatigue resistance, which can perform effective suturing, reduce the difficulty of suturing, and improve the suturing efficiency.

The aim of this project is to determine the following research content through experimental exploration in a controllable experimental environment: develop a high - performance nickel - rich Ti - 50.8Ni - 0.4V SMA, systematically study the effects of process factors such as annealing process, aging process, deformation rate, deformation temperature, and stress - strain cycle on the properties of Ti - 50.8Ni - 0.4V alloy, establish the relationship between solution - aging and annealing treatment and martensitic transformation behavior, shape - memory effect, and superelastic behavior, which is of great practical significance for adjusting the optimal heat - treatment process parameters of Ti - 50.8Ni - 0.4V SMA, and provide a theoretical basis and experimental support for the actual production and application of bendable suture needles with high strength and high superelasticity for low - temperature use.

2. Preparation Process and Technology

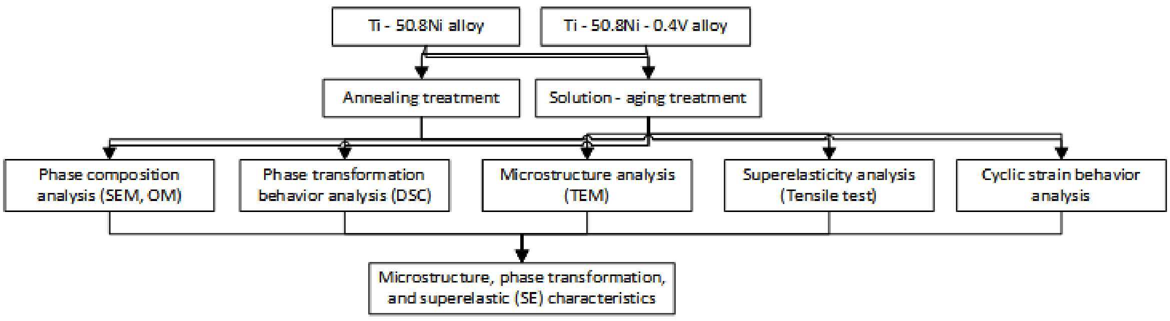

Fig 1. Technical flowchart.

As shown in the flowchart:

(1) Design nickel-rich Ti-50.8Ni alloy and Ti-50.8Ni-0.4V alloy with trace amounts of vanadium added. These alloys are melted into ingots in a vacuum induction melting furnace and then the ingots are forged into billets. Subsequently, the billets are processed through hot forging, hot rolling, cold rolling, and multiple passes of rolling to obtain a 0.27-mm-thick sheet.

(2) Employ SEM (Scanning Electron Microscope), OM (Optical Microscope), DSC (Differential Scanning Calorimeter), and TEM (Transmission Electron Microscope) to analyze the phase transformation temperatures, phase compositions, and microstructural characteristics of the Ti-50.8NiX alloys after different annealing and solution-aging treatments. Focus on researching the influence rules of different heat treatment processes on the martensitic phase transformation behavior, phase composition, thermal hysteresis of the alloys, as well as the changes in the precipitation process such as the size and dispersion of the precipitated phases.

(3) Use a tensile testing machine (equipped with a controllable temperature chamber) to analyze the superelastic properties of Ti-50.8NiX alloys after different annealing and solution-aging

treatments. Emphasize on studying the relationship between annealing, solution-aging treatments, and the functional properties of the alloys. Meanwhile, further explore the influence rules of the changes in precipitated phases during the solution-aging treatment on the microstructure and mechanical properties of the alloys.

(4) Conduct stress-strain cyclic training on the Ti-50.8NiX shape memory alloys after annealing or aging treatments. Determine the relationship between the number of cycles and cyclic energy consumption, and explore the impact of the number of cycles on the memory effect and superelastic stability of the alloys.

(5) By varying the deformation temperature and loading rate under the stress-strain state of the alloys, investigate the influence rules of the loading rate and deformation temperature on the shape memory effect and superelastic properties of the alloys.

(6) Through the above steps, fabricate arbitrarily bendable guide needles with high strength and excellent superelasticity for low-temperature applications.

3. Experimental Methods and Procedures

3.1. Experimental Materials and Preparation

The raw material used in the experiment is NiTi alloy, specifically composed of 55 wt% Ni - 45 wt% Ti. After designing the nickel - rich Ti - 50.8Ni alloy and the Ti - 50.8Ni - 0.4V alloy with a trace amount of V added, a heat - treatment process is carried out on them. The alloys are melted into ingots in a vacuum induction melting furnace and then the ingots are forged into billets. The billets are cold - rolled and then tempered at 500 °C to remove internal stress. Subsequently, through multiple - pass rolling, a sheet with a thickness of 0.27 mm is obtained. Samples are cut from the sheet for the preparation of guide needles.

Table 1. Experimental materials.

Specimen Name	Chemical Formula	Specification	Test Contents
Nickel - Titanium Alloy	NiTi	Thickness: 0.27 mm	Surface micro - morphology (SEM, OM), microstructure (TEM), phase transformation process (DSC); cyclic tensile stress - strain curve

3.2. Equipment Required for the Experiment

(1) Universal Tensile Testing Machine: SANS UTM 4000 electronic universal testing machine
(2) Fatigue Testing: ElectroForce 3200
(3) SEM (Scanning Electron Microscope): Quanta FEG 450, FEI
(4) DSC (Differential Scanning Calorimeter): DSC 8500 from PerkinElmer
(5) OM (Optical Microscope)
(6) TEM (Transmission Electron Microscope): TenaiG2F20

3.3. Sample Characterization

In this project, a scanning electron microscope (Quanta FEG 450, FEI) and an optical microscope are used to observe and analyze the surface micro - morphology of the alloy samples. Meanwhile, a transmission electron microscope (TenaiG2F20) is used to observe the microstructure, and a differential scanning calorimeter (DSC 8500 from PerkinElmer) is used to measure the phase - transformation process of the alloy. For the heat - treated NiTi alloy, a universal material testing machine (SANS UTM 4000) is used to analyze the stress - strain curves of the Ti - 50.8NiX alloy after different annealing and solution - aging treatments. At the same time, cyclic tensile tests are conducted on the alloys after different annealing and solution - aging treatments to analyze and measure their superelastic properties. Finally, an ElectroForce 3200 is used for electric - drive fatigue testing and to analyze their fatigue properties.

4. Phase Transformation and Mechanical Properties of NiTi Alloy

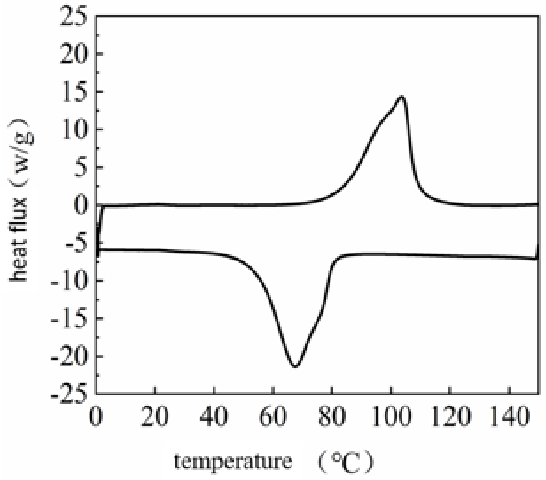

Fig 2. DSC Curve of Ni - Ti45 Specimen.

A scanning calorimeter (DSC 8500 from PerkinElmer) was used to measure the temperature transformation points of the specimen. The measured phase transformation points are as follows: the starting temperature of austenite transformation, as = 85.97 °C; the ending temperature of austenite transformation, Af = 110.94 °C; the starting temperature of martensite transformation, Mf = 55.23 °C; and the ending temperature of martensite transformation, Ms = 80.40 °C.

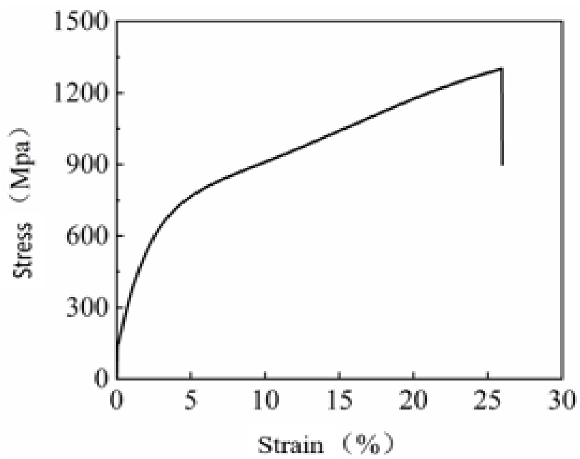

Fig 3. Tensile Stress - Strain Curve of Ni - Ti45 Specimen.

The mechanical properties of the specimen tested by the universal material testing machine are shown in Figure 3. The elongation rate reaches 26%, the tensile strength is 1300 MPa, and the critical transformation stress is approximately 767 MPa.

5. Influence of Heat Treatment on the Superelasticity of TiNi Alloy

5.1. Experimental Method

NiTi wire materials were cut into 10 - mm lengths and placed in a cyclic heat - treatment furnace for annealing under different heat - treatment processes. The tensile mechanical properties and superelasticity of the wire materials were tested on a SANS UTM 4000 electronic universal tensile testing machine. Flat - shaped chucks were used, with a pre - tightening stress of 4 MPa. The gauge length of the wire tensile specimen was 100 mm, and the tensile rate was 2 mm/min. The ambient temperature for the tensile test was 28 °C. During the superelasticity test, the total tensile strain was set to 6% and then unloaded. The parameters of the cyclic tensile test were the same as those of the single - tensile test, and the number of cycles was 10.

5.2. Experimental Results and Discussion

5.2.1. Stress - Strain Curves of Wire Materials Annealed at Different Temperatures

The curves of the superelastic property changes of the specimens after annealing at different temperatures of 400, 450, 500, 550, and 600 °C for 15 min are shown in Figure 4 - 1. It can be seen that as the annealing temperature increases, the critical stress value σs for stress - induced martensitic transformation gradually decreases. After heat treatment at 400, 450, and 500 °C, the elongation rate does not change significantly. However, when the annealing temperature exceeds 500 °C, the elongation rate begins to increase significantly. Especially after annealing at 600 °C, within a strain range of 6%, the alloy remains in the martensite re - orientation stage. When the annealing temperature is < 500 °C, as the annealing temperature increases, the wire materials undergo recovery and recrystallization processes successively. Dislocations and defects gradually decrease or disappear, and the microstructure gradually grows. Dislocations, defects, and the grain boundaries of fine grains all inhibit the occurrence of stress - induced martensite. Therefore, as the annealing temperature increases, σs decreases. When the annealing temperature is > 500 °C, the alloy has completed recrystallization, and the microstructure begins to coarsen. At this time, σs is not only affected by the annealing temperature, but also greatly influenced by the phase - transformation temperature [34]. After annealing at different temperatures, the alloys have different phase - transformation temperatures. Therefore, at room temperature, σs is more affected by the phase transformation, resulting in similar σs values near 500 and 550 °C. The significant increase in the elongation rate at 600 °C is mainly due to the fact that after the annealing temperature is higher than 500 °C, the plastic - deformation ability of the alloy greatly increases, the plastic - deformation zone becomes flatter, and the elongation rate increases significantly.

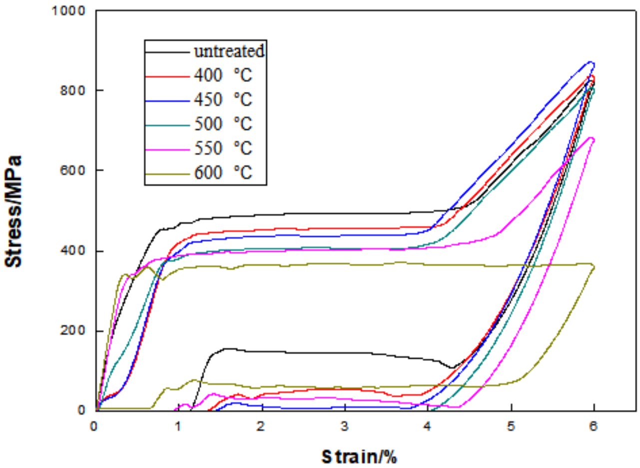

Fig 4. Stress - Strain Curves of Nickel - Titanium Wires after Annealing at Different Temperatures.

5.2.2. Stress - Strain Curves of Wire Materials after Annealing at Different Times

The curves of the superelastic property changes of nickel - titanium alloy wires after annealing at 500 °C for different times are shown in Figure 4 - 2. It can be found from the figure that after annealing at 500 °C for different times, as the holding time increases, the superelastic property decreases, while the elongation rate basically remains unchanged. This is because the alloy is a nickel - rich Ti - Ni alloy. In the initial stage of heat treatment, Ti_3Ni_4 phase or $Ti_{11}Ni_{14}$ phase precipitates. Since these fine precipitates are coherent with the matrix, the critical stress for matrix slip increases, which can enhance the strength of the matrix. As the annealing time prolongs, the size of these precipitates increases, the coherence weakens, and the strengthening effect on the matrix weakens. With the increase in the size and quantity of the precipitate particles in the matrix, the Ni content in the matrix alloy decreases, resulting in an increase in the phase - transformation temperature of the matrix [35]. Therefore, short - time and low - temperature aging is more likely to obtain better superelasticity.

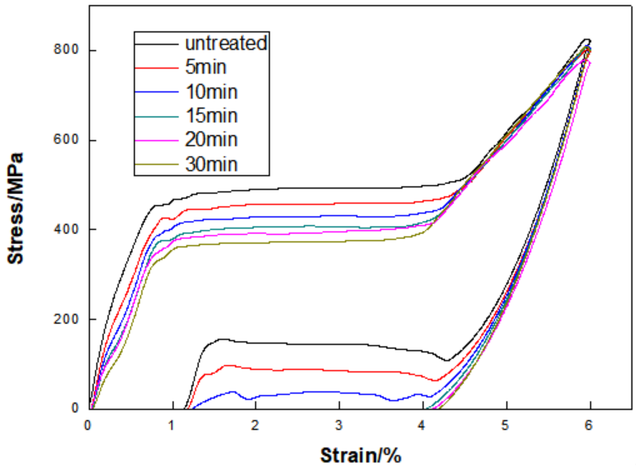

Fig 5. Stress - Strain Curves of Nickel - Titanium Wires after Annealing for Different Times.

From the mechanical property test results of the above alloy wires, it can be known that the plateau stress decreases as the aging time prolongs. This is because the critical stress for stress - induced martensite is closely related to the experimental temperature. Some studies have shown that when the experimental temperature is higher than the starting temperature of martensitic transformation, the critical stress σf for the forward transformation of stress - induced martensite can be expressed as

$$\sigma_{\mathrm{f}} = \sigma_{\mathrm{o}}^{SIM} + (T - M_S)\frac{\mathrm{d}\sigma}{\mathrm{d}T} \quad (1)$$

Correspondingly, the stress σr of the reverse transformation can be expressed as...

$$\sigma_{\mathrm{r}} = -\sigma_{\mathrm{o}}^{SIM} + (T - A_{\mathrm{f}})\frac{\mathrm{d}\sigma}{\mathrm{d}T} \quad (2)$$

In the formula, σ_{o}^{SIM} represents the minimum stress for inducing martensite at the Ms point.

Since the change trend of the plateau stress during the alloy tensile test is consistent with that of the critical stress for stress - induced martensite, the magnitude of the plateau stress also has a linear relationship with the difference between the experimental temperature and the phase - transformation temperature. In the study of the effect of aging treatment on the phase - transformation behavior of materials, we found that the phase - transformation temperatures (Ms and Af) increase with the prolongation of the aging time. Combining the formulas, it can be seen that the plateau stress decreases as the aging time prolongs. This is consistent with our experimental results.

5.2.3. Cyclic Stress-Strain Curves of Wire Materials after Annealing at Different Temperatures

Figure 4- 3 shows the cyclic stress - strain curves of wire materials after annealing at different temperatures for 10 cycles. It can be seen from the figure that after annealing at different temperatures, the cyclic deformation stress - strain curves of different wire materials exhibit obvious stress plateaus. As the number of cycle's increases, the critical stress for stress - induced martensitic transformation gradually decreases, and the critical stress for reverse transformation also decreases to a certain extent. The stress hysteresis (which represents the difference in the stress of the platforms corresponding to the loading and unloading curves at the same strain) remains stable. For the wire materials annealed at 400, 450, and 550 °C, the phase - transformation stress gradually decreases with the increase in the number of cycles and finally tends to a constant value; residual strain is only generated during the first tensile test, and no new residual strain is generated in subsequent cyclic tests. However, for the annealing processes at 500 and 600 °C, it is obvious that the residual strain has been increasing during the 10 - cycle stress - strain process. This indicates that the reverse transformation is becoming less and less complete, that is, the loss of superelasticity is becoming more and more obvious [36].

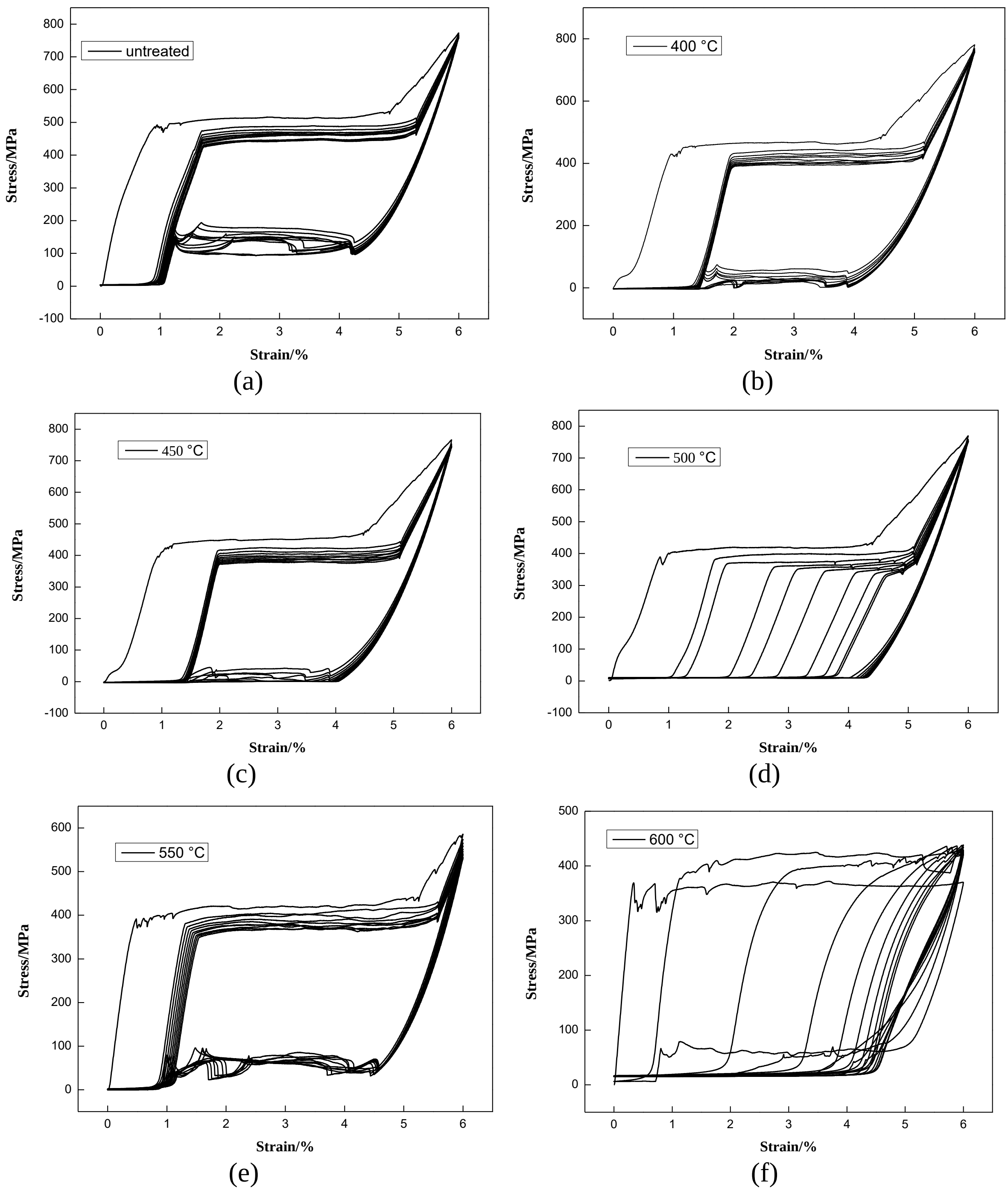

Fig 6. Cyclic Stress - Strain Curves of Ni50.8Ti49.2 Wire Materials after Annealing Processes at Different Temperatures (a) Untreated; (b) 400°C; (c) 450°C; (d) 500°C; (e) 550°C; (f) 600°C.

5.2.4. Cyclic Stress - Strain Curves of Wire Materials after Annealing for Different Times

Figure 4 - 4 shows the cyclic stress - strain curves of wire materials after annealing for different times for 10 cycles. It can be seen from the figure that stable stress plateaus also appear in the stress - strain processes of wire materials annealed for 5, 10, 15, and 20 minutes. At the same time, it can be observed that for short - term (5 - 10 minutes) heat treatment, the residual strain only appears in the first stress - strain process and does not appear in subsequent tensile tests. However, when the holding time is longer than 15 minutes, the residual strain after each tensile test continues to increase. Especially after 30 minutes, the residual strain after the first tensile test is close to 4%.

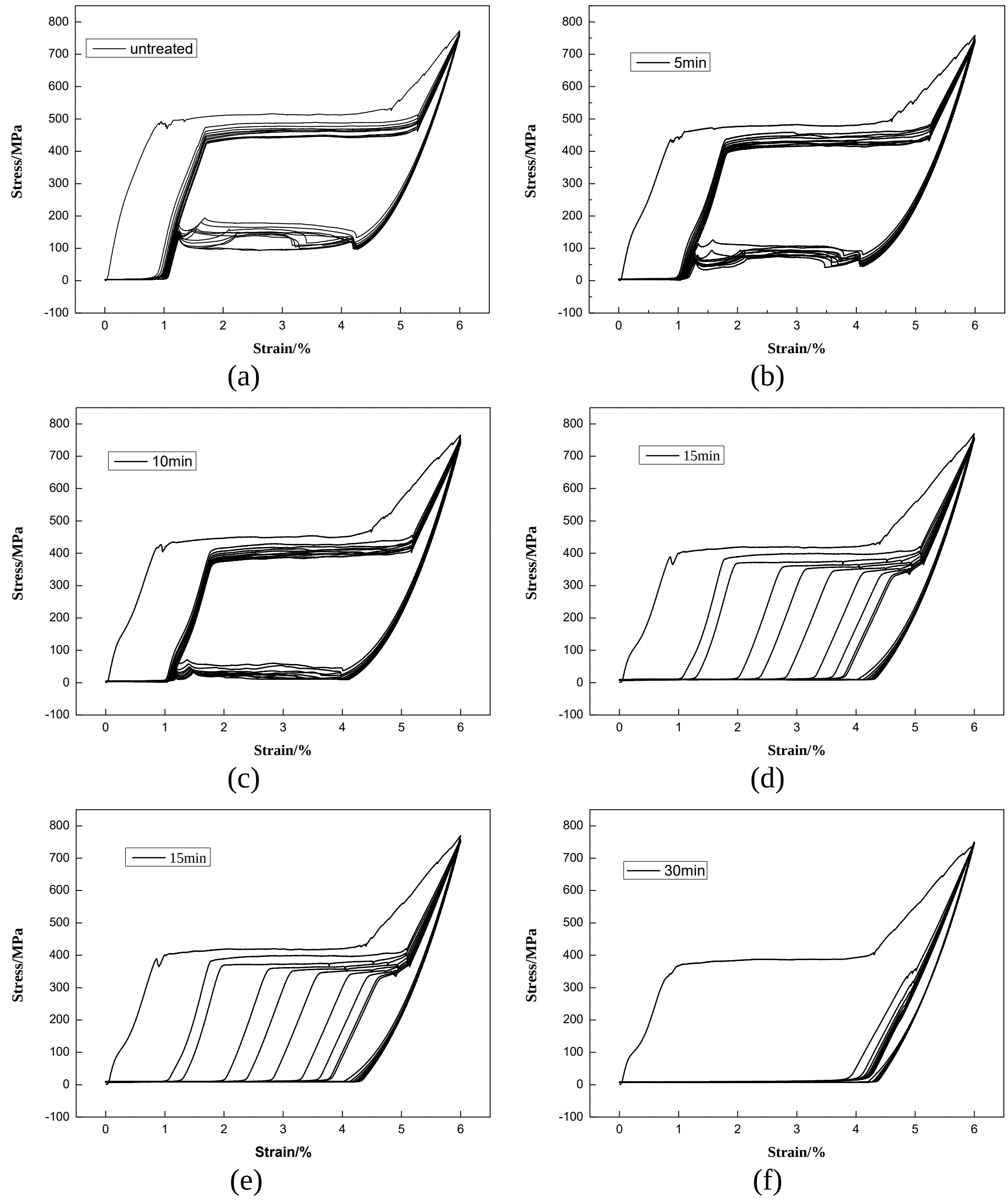

Fig 7. Cyclic Stress - Strain Curves of Ni50.8Ti49.2 Wire Materials under Annealing Processes at Different Times (a) Untreated; (b) 5 min; (c) 10 min; (d) 15 min; (e) 20 min; (f) 30 min.

6. Fatigue Performance Test of TiNi Alloy

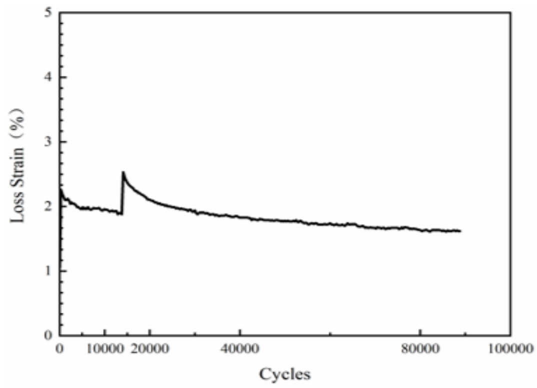

Fig 8. Fatigue Loss Curve of Ni50.8Ti49.2 Wire.

Figure 8 shows the fatigue loss curve of the wire material obtained after electrically - driven tensile tests at a fixed strength of 200 MPa. In each cycle, the tensile stress reaches 200 MPa and then is unloaded to test its fatigue performance under fixed - stress conditions. The measured fatigue life is more than 88,800 cycles. The strain loss is calculated by subtracting the recovery displacement from the tensile displacement in each cycle and then dividing by the tensile displacement. It can be found that the average strain loss in the first 15,000 fatigue cycles is about 2%, and the average strain loss per cycle in the entire fatigue process is approximately 1.7%. This indicates good fatigue life and fatigue recovery capabilities. The energy loss under a stress condition of 200 MPa is low, which is beneficial for long - term use and has little impact on the accuracy during use.

7. Conclusions

In this project, the superelasticity of the alloy was improved through heat - treatment processes. Micro - surface research was carried out with the help of a scanning electron microscope, and mechanical properties were analyzed using a universal material testing machine. Through the above research and analysis, the following conclusions were obtained:

(1) When NiTi alloy wires are annealed at 400 - 600 °C, as the heat - treatment temperature increases, the critical stress value σs for stress - induced martensitic transformation gradually decreases, the residual strain after the tensile test continuously increases, and the superelasticity of the alloy significantly decreases. When aged at 500 °C, as the aging time prolongs, σs also continuously decreases, and the residual strain after the tensile test continuously increases, resulting in a significant decrease in the superelasticity of the alloy. Therefore, low - temperature and short - time heat treatment is more likely to obtain good superelasticity.

(2) In the cyclic stress - strain curve, as the heat - treatment temperature continuously increases, the residual strain of the wire material itself becomes larger and larger, indicating that the superelasticity of the wire material is lost more and more. When the temperature is 400 and 450 °C, in the stress - strain curve, the residual strain of the wire material only occurs in the first tensile test, and almost no new residual strain is generated in the remaining cyclic tensile tests, indicating that the wire material has good continuous superelasticity. At the same time, as the heat - treatment time prolongs, the superelasticity of the wire material drops sharply. Especially when the heat - treatment holding time is 30 minutes, it is basically impossible to form a superelastic window in the stress - strain curve.

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