Design and technological capabilities of the TiNi alloy ring-shaped bundle force elements

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Abstract. The usage of layered compositions in mechanical engineering technology can ensure effective reduction of various systems vibrations and workers protection at production sites. The technology of sintering such compounds is implemented by using a miniature press SheR, acting on the shape memory effect. The paper presents the design and technological capabilities of controlling the operation of the working device power drives which are made from the TiNi alloy.

1. Introduction

Nowadays, great attention is given to the manufacture of advanced materials, intermetallic compounds, functional materials [1-3]. The usage of layered materials (sandwiches) has shown its effectiveness so that to reduce vibrations in shipbuilding and aerospace [4]. This technology was used in creation of personal protective equipment (PPE) using vibration with changing the combination of materials [5]. Metals were replaced by textiles, knitwear and leather, which became the base of the created products. The operation of combining the PPE base and a vibration-absorbing coating (VAC) required heat and pressure. The first technological solution for a single production consisted in the implementation of constant pressure on sandwiches in conditions of heating in a thermostat (Figure 1). However, this method allowed loading the furnace chamber only by half, because the rest of the space was occupied by loads that provide constant pressure. The maximum load did not exceed 300 N.

The usage of a miniature press SheR increased the furnace loading volume twice in a technological operation (Figure 2) [6]. Figure 3 shows the device prepared for the process operation.

Under the action of thermal energy the pre-deformed TiNi alloy of ring-shaped bundle force elements (RBFE) 1 restores the initial shape as a result of the shape memory effect (SME) growth and generate the batch of pieces of 5 compressing forces, which provides a diffusion connection of the base and the vibration-absorbing coating over the entire materials surface. Thus, bulk loads were replaced by a pair of drives with a total weight of 60 g, capable of creating forces up to 1200 N. Increasing the level of power impact on the processed objects made it possible to further reduce the time of the technological operation from 4 h to 2.5 h at a preheated thermostat temperature of 400 K. Thus, the total amount of pieces produced in a single shift from one furnace chamber grew from 2 batches with a volume of $V_1$ to 3 batches with a volume of $V_2 = 2V_1$. As a result, the efficiency of technological operation in the thermostat increased 3 times. The aim of the work was to increase the efficiency of RBFE power drives in order to design technological processes.
The type of crystal lattice changes due to the process of martensitic transformation in metals with shape memory. For example, TiNi has a face-centered tetragonal lattice in a low-temperature martensitic state. Direct transformation during cooling occurs in the temperature range of \([M_s, M_f]\) \([7]\). The alloy lattice is rearranged into a body-centered cubic one when it heated in the temperature range of \([A_s, A_f]\) \([7]\). Thus, the material is transferred completely into the austenitic state. The temperatures of martensitic transformations can strongly depend on the chemical composition of the alloy.

A significant feature was noticed by observing the development of deformation processes of «metal muscles» during thermal cycling with the implementation of the material transformation from the martensitic phase into the austenitic phase and back. During the SheR heating, RBFE, which were loaded in a low-temperature state, began to deform under the force action from the compressed batch of the side of pieces. The characteristic size of the «metal muscles» \(d(t)\) (Figure 4) was increasing. This process happens due to the fall of the elastic modulus in the RBFE material that occurs during the restructuring of the phase lattice. The next stage of shape change was the opposite process due to the shape memory effect.

The technological situation in a special dynamometer LIND was simulated \([8]\). In the second thermocycle, the growth of shape change \(d(t)\) decreased. And in the next thermal cycle this process was
absent. At the same time, the «training» of «metal muscles» was carried out, which means the buildup of their power capabilities. The force-force coefficient $k_{FF} = \frac{F_{SME}}{F_0}$ [8] (where the maximum interaction force $F_{SME} = F_0 + K \Delta$, spring rate $K = 100 \text{ N/mm}$), which characterizes the fraction of the maximum generated force $F_{SME}$ relatively the active deformation force in the martensitic state $F_0$, which reached a value of 3.3. Thermal cycling changes the order of deformation processes. These results and the data presented in papers [9, 10] noticed the possibility of using the heterophase state of the TiNi alloy during direct martensitic transformation and transformation plasticity [11] to control the deformation-power characteristics of the «metal muscles».

2. Results and Discussion

The properties of two pairs of samples from a 2 mm wire in the diameter were investigated to determine the factors, which give the possibility to regulate and to predict the behavior of the RBFE. «Metal muscles» from alloys TiNi50.35at.% and TiNi50.45at.% were studied. The LIND dynamometer was used for these experiments (the diagram in Figure 4). Power elements consisted of five ring shape closed coils. Deformation of the RBFE was performed at the minimum temperature of the thermal cycle. The force interaction changed with the steel spring of the LIND dynamometer counterbody 2. These changes made possible to increase the characteristic size $d(t)$. Because a RBFE pair is used in technological devices of the SheR type, in LIND two samples 1 were simultaneously tested and placed in parallel planes symmetrically relative to counterbody 2. The dynamometer with power elements was kept for at least 10 hours under isothermal conditions at a minimum temperature of the cycle $T_{min}$ before each thermal cycle starts. In the experiments, the maximum value of forming $\Delta_{SME}$, due to the shape memory effect, was determined during thermal cycling under conditions of force interaction with the counterbody. It was necessary to conduct a series of experimental studies with each of the samples: in the temperature range from 299 K to 403 K, when at $T_{min}$ the materials of the power elements were in the austenitic state near $M_s$. Therefore, the deformation of the materials caused the induction of a certain amount of the martensitic phase. Further, the samples were thermally cycled in the temperature range from 279 K to 403 K, when at $T_{min}$ the alloys transformed a partial phase transition, that is, they were in a heterophase state. With thermal cycles from 271 K to 403 K RBFE materials change into direct martensitic transformation to a much greater degree. Table 1 presents the results of the experiments.

| Figure 3. Technological press operating at the SME: 1– RBFE, 2, 6 — grip, 3 — movable plate, 4 — base, 5 — batch of pieces |
| Figure 4. RBFE’s strain scheme in dynamometer LIND: 1 – RBFE, 2 – counter-body (coil spring), 3 – movable plate, 4 – regulating movable plate, 5 – measuring system, $d(t)$ – characteristic size of RBFE |

Table 1. The deformation-power characteristics of RBFE during deformation and thermal cycling
| Cycle | RBFE from TiNi50.35at.% | RBFE from TiNi50.45at.% |
|-------|----------------|-------------------|
|       | $F_0$, N | $d_1$, mm | $\Delta_{SME}$, mm | $F_{SME}$, N | $F_0$, N | $d_1$, mm | $\Delta_{SME}$, mm | $F_{SME}$, N |
| 1     | 215      | 66         | 1.05                | 315.5       | 180      | 66.5        | 2.4                | 420          |
| 2     | 300      | 65.75      | 1.1                 | 410         | 240      | 66.9        | 2.8                | 520          |
| 3     | 390      | 66.5       | 0.9                 | 480         | 320      | 67.8        | 3.3                | 650          |
| 4     | 480      | 67.4       | 1.2                 | 600         | 360      | 69.1        | 3.8                | 740          |
| 5     | 620      | 68.3       | 1.8                 | 800         | 390      | 71.1        | 4.4                | 830          |
| 6     | 700      | 68.1       | 1.65                | 865         | 440      | 72          | 5                  | 940          |
| 7     | 750      | 68.8       | 1.85                | 935         | 530      | 71.5        | 4.5                | 980          |
| 8     | 820      | 68.9       | 1.95                | 1015        | 490      | 72          | 4.9                | 980          |
| 9     | -        | -          | -                   | -           | 600      | 73          | 3.95               | 995          |
| 10    | -        | -          | -                   | -           | 650      | 72.9        | 4.05               | 1055         |

| Cycle | Temperature of deformation $T_{\text{min}} = 279$ K |
|-------|----------------------------------|
|       | $F_0$, N | $d_1$, mm | $\Delta_{SME}$, mm | $F_{SME}$, N | $F_0$, N | $d_1$, mm | $\Delta_{SME}$, mm | $F_{SME}$, N |
| 1     | 80      | 68.45      | 2.6                 | 340         | 210      | 66.5        | 2.45               | 455          |
| 2     | 180     | 69.15      | 3.1                 | 490         | 180      | 67.7        | 4.2                | 600          |
| 3     | 240     | 70.25      | 3.5                 | 590         | 200      | 69.1        | 4.1                | 610          |
| 4     | 430     | 71.75      | 3.9                 | 820         | 210      | 70          | 4.8                | 690          |
| 5     | 550     | 73.25      | 4.3                 | 980         | 260      | 71          | 4.95               | 755          |
| 6     | 650     | 74.75      | 4.8                 | 1130        | 360      | 71.6        | 5.1                | 870          |
| 7     | 740     | 76.35      | 5.3                 | 1270        | 420      | 72.7        | 5.3                | 950          |
| 8     | -       | -          | -                   | -           | 510      | 74.4        | 5.2                | 1030         |

| Cycle | Temperature of deformation $T_{\text{min}} = 271$ K |
|-------|----------------------------------|
|       | $F_0$, N | $d_1$, mm | $\Delta_{SME}$, mm | $F_{SME}$, N | $F_0$, N | $d_1$, mm | $\Delta_{SME}$, mm | $F_{SME}$, N |
| 1     | 90      | 67.5       | 1.5                 | 240         | 70       | 67.6        | 3.55               | 425          |
| 2     | 160     | 68.4       | 2.2                 | 380         | 80       | 68.1        | 3.8                | 460          |
| 3     | 270     | 68.7       | 2.3                 | 500         | 80       | 69          | 4.3                | 510          |
| 4     | 300     | 69.9       | 2.85                | 585         | 140      | 69          | 4.3                | 570          |
| 5     | 340     | 72.2       | 3.6                 | 700         | 120      | 69.9        | 4.7                | 590          |
| 6     | 410     | 73.1       | 4                   | 810         | 170      | 70.4        | 5                  | 670          |
| 7     | 420     | 75.9       | 5                   | 920         | 140      | 71.4        | 5.7                | 710          |
| 8     | -       | -          | -                   | -           | 120      | 71.9        | 5.9                | 710          |

*Table 1.*
The maximum generated force during the development of the SME was 510 N. Thus, the framework. Thermocycling of RBFE was performed for the TiNi50.45at.% alloy in the same temperature cycles, 90 N to 420 N. The ratio of the counterbody from 180 N to 500 N. A displacement of 4 mm can also be carried out at elevated loads from 600 N to 650 N. In both cases, the maximum force created by experimental drives reached ~ 1000 N.

The force of the counterbody to the operation of RBFE from TiNi50.35at.% alloy was changed from 80 N to 740 N at the minimum thermal cycling temperature of 279 K. At the same time, the deformation capacity grew from 2.6 mm to 5.3 mm, and the maximum generated force as a result of thermal cycling was 1270 N. The possibility to increase the deformation parameters for power drives made from TiNi50.45at.% alloy, while maintaining constant force interaction with the counterbody was ~ 200 N at $T_{\text{min}}$, was found. In this mode, the maximum parameter $\Delta \sim 5$ mm was reached, which remained virtually unchanged with a further increase in $F_0$ from 210 N to 510 N.

Carrying out the experiment with RBFE from the TiNi50.35at.% alloy at a minimum temperature of 271 K, it was possible to carry out $\Delta_{\text{SME}}$ displacements in the range from 1.5 mm to 5 mm with loads from 90 N to 420 N. The ratio $F_0$ and $d_1$ differed significantly from deformation at $T_{\text{min}} = 279$ K. Thermocycling of RBFE was performed for the TiNi50.45at.% alloy in the same temperature framework. With loads of ~ 80 N in three cycles, the value of the $\Delta_{\text{SME}}$ parameter of 4.3 mm was reached. The maximum generated force during the development of the SME was 510 N. Thus, the $k_{PF}$ coefficient exceeded number 6. Further expansion of the deformation parameters to 7.2 mm took place at loads of

| Cycle | $F_0$, N | $d_1$, mm | $\Delta_{\text{SME}}$, mm | $F_{\text{SME}}$, N | $F_0$, N | $d_1$, mm | $\Delta_{\text{SME}}$, mm | $F_{\text{SME}}$, N |
|-------|----------|-----------|----------------|-------------------|----------|-----------|----------------|-------------------|
| 1     | 90       | 67.5      | 1.5            | 240               | 70       | 67.6      | 3.55           | 425               |
| 2     | 160      | 68.4      | 2.2            | 380               | 80       | 68.1      | 3.8            | 460               |
| 3     | 270      | 68.7      | 2.3            | 500               | 80       | 69        | 4.3            | 510               |
| 4     | 300      | 69.9      | 2.85           | 585               | 140      | 69        | 4.3            | 570               |
| 5     | 340      | 72.2      | 3.6            | 700               | 120      | 69.9      | 4.7            | 590               |
| 6     | 410      | 73.1      | 4              | 810               | 170      | 70.4      | 5              | 670               |
| 7     | 420      | 75.9      | 5              | 920               | 140      | 71.4      | 5.7            | 710               |
| 8     | -        | -         | -              | 120               | 71.9     | 5.9       | 710            |                   |
| 9     | -        | -         | -              | 160               | 72.3     | 6.2       | 780            |                   |
| 10    | -        | -         | -              | 160               | 73.3     | 7.2       | 880            |                   |
| 11    | -        | -         | -              | 150               | 74       | 7.5       | 900            |                   |
| 12    | -        | -         | -              | 230               | 74       | 7.2       | 950            |                   |
| 13    | -        | -         | -              | 270               | 74.4     | 7.5       | 1020           |                   |
| 14    | -        | -         | -              | 290               | 75       | 8         | 1090           |                   |
| 15    | -        | -         | -              | 310               | 75.3     | 7.9       | 1100           |                   |
| 16    | -        | -         | -              | 330               | 75.8     | 7.8       | 1110           |                   |
| 17    | -        | -         | -              | 340               | 76.7     | 8.3       | 1170           |                   |
| 18    | -        | -         | -              | 420               | 76.8     | 7.8       | 1200           |                   |

Carrying out the deformation of RBFE from the TiNi50.35at.% alloy at a temperature of 299 K a small displacement of SME was found in the range from 1 mm to 2 mm under thermal cycling conditions under preloading from 215 N to 820 N. Under these conditions, RBFE from TiNi50.45at.% alloy showed SME displacements in the range from 2.4 mm to 5 mm with initial force contact with the counterbody from 180 N to 500 N. A displacement of 4 mm can also be carried out at elevated loads from 600 N to 650 N. In both cases, the maximum force created by experimental drives reached ~ 1000 N.
~ 150 N, the ability to generate efforts increased to 900 N. In this area, the $F_{SME}$ remained sixfold superior over $F_0$. Further, thermal cycling continued with a change in $F_0$ from 230 N to 420 N. This made it possible to increase the deformation capabilities of the «metal muscles» up to 8 mm, and their power properties reached 1200 N.

In the same conditions of thermal impact, two RBFE pairs of different chemical compositions have different deformation-force characteristics. There is a possibility to increase the ring-shaped bundle force elements from the TiNi50.45at.% alloy; deformation-power properties with $F_0$ efforts are 6 times smaller than those generated during heating. This fact implies saving money in RBFE preparation for the operation due to the usage of less powerful deformation equipment.

3. Conclusion
The following conclusions based on the results of the work can be made.

Under the conditions of thermal cycling using constant force interaction with the counterbody it is possible to achieve a significant reduction in the forces activating the shape memory effect by choosing the preparation temperature near the lower limit of the interval $[M_S; M_f]$ or lower $M_f$.

The results analysis showed that when technological charts with deformation-force characteristics of RBFE were drawn up, it was necessary to take into account all factors affecting the thermoelastic martensitic transformation in alloys with shape memory effect, which makes it necessary to introduce individual passports for «metal muscles».

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