Effect of High Strain Rate on TiNi Shape Memory Alloys

RAZOV A

(Saint-Petersburg State University, Saint-Petersburg 198504, Russia)

Abstract: In recent years, an increasing interest in shape memory effects and TiNi alloys can be observed from researchers, engineers and designers due to improving technologies of manufacturing and processing of such alloys. There is also some progress in the understanding of shape memory alloys behavior both during and after high strain rate loading. This paper presents the state-of-the-art in the investigations of TiNi-shape memory alloys behavior at high strain rate loading. Chronology of investigations is also presented. Thermo-mechanical response at various temperatures and strain rates is observed. Effect of high strain rate on functional properties of TiNi-shape memory alloys is presented. In order to describe dynamic mechanical behavior of TiNi shape memory alloy in martensitic state an attempt to apply the principles of yielding based on the concept of the so called "incubation time" was suggested. For this purpose magnetic pulse loading was used. This method allows controlling the amplitude of electric impulse and its duration. To determine the parameters of "incubation time" concept the critical amplitudes of force leading to inelastic strain of TiNi in martensitic state was determined and the characteristic time of this process was calculated.

Key words: shape memory effect; TiNi alloys; high rate strain; functional properties; incubation time

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Use of materials with shape memory effect (SME) in the technique currently receives a new impetus by the discovery of new alloys, a considerable progress in the production of semi-finished products and technologies in their processing, overcoming conservative thinking engineers, designers and managers. However, many areas of modern application development aim to miniaturize and reduce the response time of devices, the use of fast processes. In this regard, a great importance is the study of thermo-mechanical and functional properties of the alloys with SME in dynamic conditions, when the deformation occurs at speeds of about $10^2 \div 10^3$ s^{-1} and above, or for a quick response of the working elements they are heated at high speed. The results of such studies may also be useful in developing technologies and the manufacture of materials with the SME.

The first studies of dynamic properties of TiNi-alloys, conducted mainly by analogy with studies of conventional materials, were directed on determination of the deformation diagrams during dynamic loading at various temperatures. For example, in [1] the alloy Ti-51at.% Ni annealed in vacuum at 673 K for 1 h was investigated at high strain rate 2×10^2 – 7×10^2 s^{-1} in compression mode. The split Hopkinson pressure bars (SHPB) technique was used. The temperatures were varied from 201 K to 366 K, while the total strain in each experiment was about 4%. The resulting dependence of the stresses corresponding to 2% strain on the temperature in the case of dynamic loading has

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Author biography: RAZOV A (1956−), male, professor, research domain: shape memory alloys. E-mail: razov@smel.math.spbu.ru

qualitatively the same shape as for the quasi-static loading, which was performed at 10^{-4} s^{-1}. This dependence has a minimum in the temperature range between *Ms* and *As*. The stresses at dynamic loading were always higher in the 50 – 100 MPa than at quasi-static loading. The second sharp turn at the dependence was caused by an intermediate rhombohedral R-phase. It was noted that the recovering of the strain after dynamic loading was the same as after the quasi-static deformation. In [2] the TiNi alloy with characteristic temperatures *Mf* = 39 ℃, *Ms* = 59 ℃, *As* = 74 ℃, *Af* = 93 ℃ was investigated at high rate compression up to 3 000 s^{-1} at room temperature to about 20% total strain. It was noted that the quasi-static and dynamic diagrams in compression up to 5% strain is almost the same. Then the dynamic diagram exceeds the quasi-static one for a 250 – 300 MPa. It was mentioned that the stabilization of martensite was observed regardless of the strain rate, which led to the conclusion that the mechanisms of deformation of TiNi alloy in the martensitic state does not depend on the rate of loading. TiNi alloy in the super-elastic state at high-rate loading was first investigated in [3]. The Ti-55, 8% Ni alloy (SE508, NDC) with characteristic temperatures *Af* = 5 – 18 ℃, *Md* ≅ 150 ℃ was investigated. The SHPB technique with pulse shaper was used. Strain rate was varied from 130 s^{-1} to 750 s^{-1}. Comparison of the quasi-static and high rate loading showed that the super-elastic properties depend on the loading rate. Under quasi-static loading at rate of 10^{-3} s^{-1} up to 3% strain the recovering was complete, while after dynamic loading the super-elastic loop was not closed, but a complete recovering of the strain took place in some time (from several seconds to several hours). In [4] the Ti-50.4at.% Ni alloy with characteristic temperature *Af* = 296 K was investigated at room temperature using asplit Hopkinson pressure bars with strain rate from 5 800 s^{-1} to 17 600 s^{-1}. The influence of additional pulse shaper was investigated in details. It was shown that the use of pulse shaper is necessary to obtain relatively constant strain rate of TiNi alloy. It was established that with increasing strain rate up to 10^3 s^{-1} the austenite to martensite transformation initiating stress increases linearly, increasing by about 500 MPa. A further increase in strain rate leads to a sharp increase in these stresses. Investigation of the structure of the alloy showed that at this point there is a change of deformation mechanism (from the formation of stress induced martensite to dislocation deformation of austenite phase). The effect of annealing for 30 min at 296 K, 473 K, 573 K, 723 K, 823 K, 873 K, 923 K of TiNi alloy with the characteristic temperature *Af* = -10 ℃ on the superelastic properties under high rate compression was investigated in [5]. Tests were carried out at temperatures range from 77 K to 400 K; the strain rate was varied from 10^3 s^{-1} to 4 200 s^{-1}. Transformation stress at which the direct martensitic transformation start under load decreases with increasing annealing temperature from about 800 MPa after annealing at 300 K to 500 MPa after annealing at 873 K. It was established that the energy dissipation in dynamic and quasi-static cases were about the same. However, with repeated loadings super-elastic changes in the dynamic case is less than in the quasi-static one. In addition, it was noted that the strain rate during unloading was poorly controlled and in all tests was about 10^2 s^{-1}. In [6] Ti-55, 6% Ni (NDC SE508) alloy with characteristic temperatures *Mf* = -36 ℃, *Ms* = -8 ℃, *As* = -23 ℃, *Af* = +2 ℃ was investigated by tensile and compressive strain at a rate of about 1 200 s^{-1} using the split Hopkinson pressure bars with and without a pulse shaper. The loading was carried out at different temperatures: -196 ℃, -100 ℃, -50 ℃, 0 ℃, CT, 100 ℃, 200 ℃, 300 ℃, 400 ℃. The difference in the behavior of the alloy in tension and compression at high rate loading was discussed.

All the above-listed works did not pay attention to the influence of high rate loading on the functional properties of TiNi alloys, the one-way and two-way shape memory effects, recovery stresses. For one of the first papers in which the question of whether the shape memory effect after the dynamic loading was studied, should be attributed to [7]. In the experiments described in this paper, the discs 40 mm in diameter and 10 mm thick made of equiatomic TiNi alloy were subjected to impact by flat projectile with a velocity of 100 m·s^{-1} from a gas gun at different temperatures. On the opposite side of the disc a suspended steel ball was positioned. This ball deformed the disc during impact and created an imprint on it surface. At room temperature TiNi alloy was in martensitic state and subsequent heating led to the initiation of the shape memory effect and reduce the depth of indentation. Comparison of the quasi-static and dynamic experiments showed that the strain recovering due to SME in the latter case was approximately 10% higher. The first studies of the two-way shape memory initiated by dynamic deformation, and its comparison with the two-way shape memory obtained after quasi-static deformation were carried out in [8]. The 1 mm thick target made of equiatomic TiNi alloy was subjected to impact by flat projectile with a velocity of 100 m·s^{-1} from a gas gun at room temperature. Then the samples with dimensions of 50 mm×5 mm×1 mm were cut from the target and were tested in three-point bending mode, conducting thermal cycling through the temperature range of martensitic transformations. In the quasi-static case, the plate in the martensitic state was deformed in the same mode. It has been found that the two-way shape memory after shock loading higher than after quasi-static loading. In addition, it has been established that the two-way shape memory formed during dynamic deformation, more resistant to external counteracting stresses than after quasi-static effects.

Unfortunately, these works did not give precise quantitative result on change in the functional properties of TiNi alloys under dynamic loading.

The first systematic study of the influence of high rate loading on SME and two-way shape memory was carried out in [9]. Cylindrical samples of 5 mm in length and diameter made of Ti-50.8at.% Ni alloy were used. After annealing at 773 K for 1 h, samples were compressed in the martensitic state at room temperature at different strain rates. Quasi-static deformation by compression at a speed of 10^{-3} s^{-1} was performed on the test machine INSTRON. Dynamic loading was performed using the split Hopkinson pressure bars technique. The pulse duration in all experiments was about 120 μs, and the strain rate was varied from 3×10^2 s^{-1} to 1×10^3 s^{-1}, 5×10^3 s^{-1}. After straining the specimens were thermo cycled at the rate near 1 K·min^{-1}. At the first heating the strain recovery was observed due to shape memory effect, while at the subsequent cycles of cooling and heating, the variation of length was resulted from the repeated two-way shape memory. Fig. 1 shows the dependence of shape memory effect on residual strain and Fig. 2 represent the dependence of two-way shape memory on irreversible plastic strain.

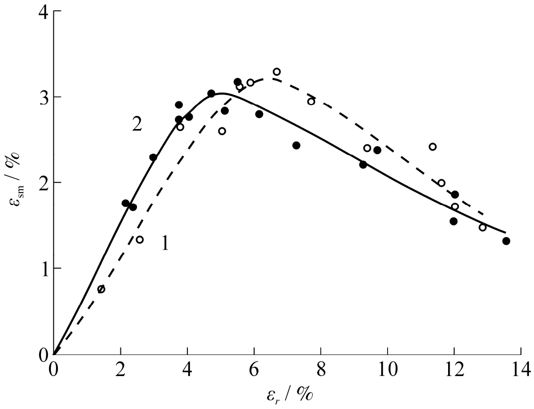


Fig. 1 Dependence of the shape memory effect on the preliminary residual strain after quasi-static 1 and impact 2 loading

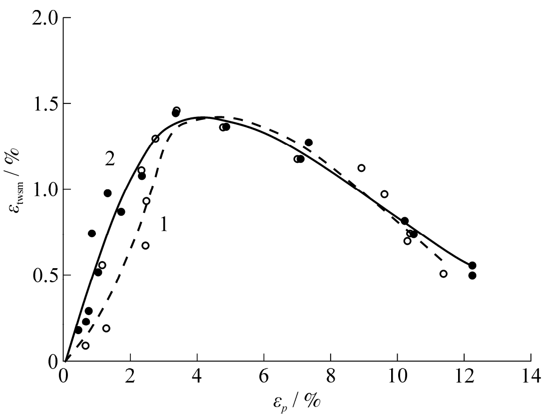
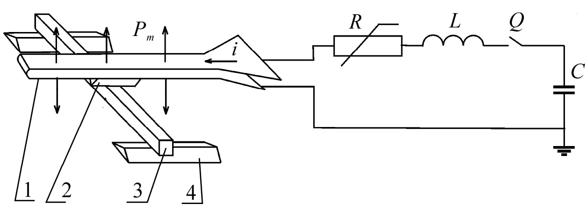


Fig. 2 Dependence of the two-way shape memory effecton the irreversible plastic deformation strain after he quasi-static 1 and impact 2 loading

It should be noted that the maximum SME strain under dynamic loading is shifted to smaller residual strains in comparison with the quasi-static loading. When the residual deformation is less than 5% the shape memory effect after the dynamic compression is more complete than after quasi-static loading, and when residual deformation more than 6% the situation is reversed. The situation with two-way shape memory is very similar. When the plastic strain is less than 4% the two-way shape memory after the dynamic compression is more than after quasi-static loading.

During the deformation of alloys with SME two processes can simultaneously develop-deformation due to martensitic inelasticity (twinning, reorientation of martensite, the formation of stress-induced martensite) and conventional dislocation plasticity. In order to determine the characteristic parameters of these processes the magneto-pulse technique and the theory, based on the concept of "incubation time"[10] were used. The dynamic three-point bending tests were carried out using magneto pulse installation with energy content of up to 15 kJ[11]. This installation allowed generating impulses of pressure with durations of microsecond and amplitudes up to 2 GPa. The pressure pulse is passed from the copper buss to the specimen through triangle steel striker (Fig. 3). Diameter of wire made of equiatomic TiNi alloy, annealed at 500 °C during 1 h (Mf = 36.5 °C) was 2 mm, distance between supports (2L) has been varied in the range of 26-49 mm.



P_m: pressure initiated by magnetic field, i: current, C: capacity, Q: switchboard, R: formative vylite resistor, L own inductance of pulse current generator; 1: Output bus, 2: striker, 3: investigated sample, 4: supports

Fig. 3 Scheme of magneto-pulse installation and scheme of loading

In each test the residual deflection and force amplitude have been measured. In each series we determined the critical force FCR by extrapolation to the zero deflection. Fig. 4 presents the results of the one of the series of testing. Threshold stresses in each case were calculated based on elastic beam theory and their values were obtained in the range 300－900 MPa for pulse durations between 400 ms and 800 ms (Fig. 4).

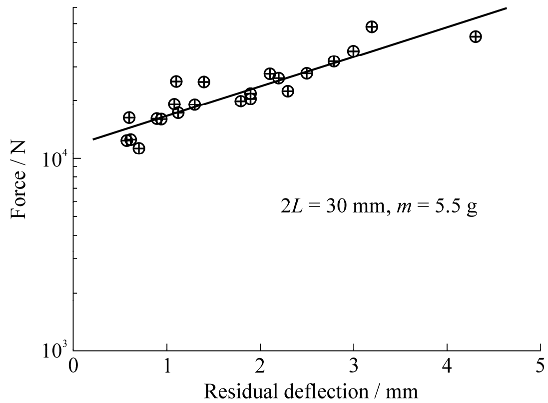


Fig. 4 Determination of the critical force amplitude

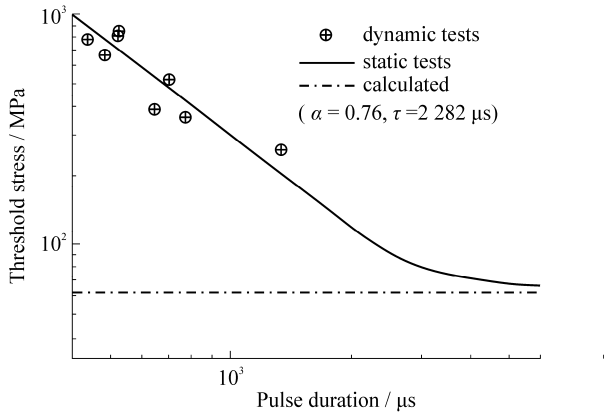


Fig. 5 Dependence of threshold stress on pulse duration

After heating of the samples it was found that the critical force FCR, initiating martensitic inelasticity (reversible channel of the deformation) and a normal dislocation plasticity are different from each other. For example, for the experiment with 2L=30 mm and striker mass m=6,7 g the force that initiates the shape memory effect was equal to 17,1 kN, and the force that initiates dislocation plasticity was equal 18,8 kN. The incubation time τ of transient process was calculated on the base of experimental data. Its value about 2 ms characterizes the range of appearance of dynamic properties of TiN alloy[11].

The currently available data shows strain rate sensitivity of the thermo-mechanical and functional properties of the TiNi shape memory alloys.

High strain rate loading of TiNi alloys can lead both to an increase in functional properties and to their suppression.

There is still no complete answer to the question about the quantitative relationship between shape memory effects and strain rate, about their dependencies on value and mode of straining for different temperatures.

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TiNi 形状记忆合金的高应变率效应

RAZOV A

（圣彼得堡国立大学，俄罗斯 圣彼得堡 198504）

摘要：近年来由于制造加工技术的改善，形状记忆效应和 TiNi 合金得到研究者、工程师和设计人员越来越多的关注．对形状记忆合金在高应变率下行为的理解取得了较大的进展．文章回顾了钛镍形状记忆合金在高应变率加载下行为的研究进展，并给出了研究年表．观测了在不同温度和应变率下的热－力学响应，以及高应变率对 TiNi 形状记忆合金的功能特性的影响．提出基于屈服准则来描述马氏体 TiNi 形状记忆合金的动态力学行为．在实验中通过控制电脉冲的幅度和宽度，确定导致马氏体 TiNi 合金非弹性应变的临界载荷幅值和特征时间，以及确定基于“孵化时间”概念的屈服参数．

关键词：形状记忆效应；TiNi 合金；高应变；功能特性；孵化时间

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