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Temperature evolution during tensile test of TiNi shape memory alloy

S.P. GADAJ ([1]), W.K. NOWACKI ([1]), H. TOBUSHI ([2])

([1]) *Polish Academy of Sciences*
Center of Mechanics and Information Technology
Institute of Fundamental Technological Research
Świętokrzyska 21, 00–049 Warszawa, Poland

([2]) *Department of Mechanical Engineering*
Aichi Institute of Technology,
1247 Yachigusa, Toyota 470–03, Japan

EXPERIMENTAL RESULTS containing both the mechanical characteristics and the changes of temperature obtained during tensile test of TiNi shape memory alloy strained at various strain rates have been presented. The investigations were carried out at room temperature ($\approx$ 295 K) and at chamber temperature equal to 333 K. The temperature changes were measured in a contactless way by recording the infrared radiation emitted by the surface of the sample. It was found that during loading at room temperature, the phase transformation process is homogeneous but at temperature 333 K the process seems to be heterogeneous. The martensitic transformation was accompanied by an increase in temperature. Both the stresses and the temperature changes were higher for the tests carried out at elevated temperature. Decreases in temperature during unloading were higher too. For tests carried out in the same conditions, the temperature increments in the range of the martensitic transformation plotted as a function of stress, turned out to lie on the same curve, independently of the strain rate.

1. Introduction

THE MECHANICAL PROPERTIES of shape memory alloys (SMA) during uniaxial tensile test, are strongly temperature – dependent. When SMA is tested above its transformation temperature A_f, martensite can be stress-induced and then, after unloading, the material transforms to austenite at a lower stress; the tensile specimen after crossing the hysteresis loop returns to the initial state. This effect is related to dissipation of energy and is known as pseudoelasticity (PE) [1, 2].

At temperatures below A_f, stress-strain curve is governed mainly by the martensite transformation: the strain in the specimen will not completely recover even after the stress removal. This strain can be almost completely eliminated by

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heating the specimen to the temperature above A_f. This phenomenon is known as the shape memory effect (SME) [1].

The thermomechanical behaviour of SMA was modelled with one- [2] or three-dimensional models [3, 4]. The models describe mechanical behaviour of the material under arbitrary condition of loading. To integrate the constitutive laws obtained from these models, the mechanical characteristics obtained from experiments are necessary. There are many interesting experimental papers concerning the shape memory alloys deformed under various rates of strain and various temperatures (e.g. [5, 6, 7, 8]). Their goal was to investigate the influence of these factors on PE and SME characteristic behaviour.

In reality, the hysteresis loop that has been observed during PE examination and the stress-strain curve registered during SME monitoring, indicate the mechanical energy dissipation [2, 9, 10]. The strain energy dissipated in the material causes an increase in temperature which can change the phase transformation process. There are few papers in which such process has been considered. For example, in [11] the temperature changes have been considered but temperature was measured there only in the range 1% of elongation. W. HUANG [12] measured the temperature during tension tests of NiTi wire using thermocouples placed in some points of the sample. He observed differences in temperature in the points what indicates the phase transformation fronts movement. Nucleation and propagation of phase transformation fronts during loading and unloading of NiTi alloy in temperature above A_f have been also observed by J.S. SHAW [13] using the infrared camera.

During fatigue test of TiNi shape memory alloy the changes of temperature were measured by H.TOBUSHI *et al.* [14, 15]. A thermocouple was used there to determine the temperature changes. It was noticed that temperature increases both with the increasing number of cycles (especially in the first 500 cycles) and with the increasing strain amplitude. The increments of temperature averaged over a cycle are small but significant. It seems however, that the applied measuring method causes a reduction of the temperature increments.

The purpose of this paper is to present experimental results of the study of thermomechanical coupling during loading and unloading of TiNi shape memory alloy in the range of martensitic transformation. The investigations were carried out both at ambient temperature (295 K) and at chamber temperature equal to 333 K. The temperature changes were measured in a contactless way, by recording the infrared radiation emitted by the surface of the sample.

2. Experimental procedure

The investigations were performed on the sheet samples: 240 mm × 6 mm × 0.5 mm, Ni 55.3wt% and the balance Ti shape memory alloy, produced by

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Furukawa Electric Co. The temperature A_f of this material was about 340 K. Before testing the samples were annealed at 180°C during 10 min. The sample was placed in a specially designed grip, fitted in the tensile testing machine. Its elongation was measured by an extensometer; the measured gauge length was 178.5 mm. The samples were first loaded to the range a little above the martensitic transformation, and then unloaded with the same rate of deformation.

The experiments were performed in room temperature (about 295 K) and in the thermal chamber at temperature 333 K. In the case of room temperature, the samples were tested at four , specially chosen strain rates: $0.47 \cdot 10^{-3}$ s^{-1}, $0.93 \cdot 10^{-3}$ s^{-1}, $1.87 \cdot 10^{-3}$ s^{-1} and $4.67 \cdot 10^{-3}$ s^{-1}. These rates should be high enough in order to provide sufficiently high temperature increments, measurable by the used thermovision set. In the case of temperature 333 K the samples were tested at three strain rates: $0.93 \cdot 10^{-3}$ s^{-1}, $1.87 \cdot 10^{-3}$ s^{-1} and $4.67 \cdot 10^{-3}$ s^{-1}. In these conditions, the specimens were observed by thermovision camera through the silicon window placed in the wall of the thermal chamber.

In the course of the straining, the load and the deformation vs. time, the stress-strain relations and the distributions of infrared radiation, emitted by the sample's surface (size 6 mm × 100 mm), were continuously registered. The distribution of infrared radiation was measured using the thermovision camera coupled to a computer system of data acquisition and conversion. The system allows us to obtain the thermovision pictures (thermograms) with various precision which are the basis for analysis of the temperature distributions of the examined surface. A thermovision camera scans the examined specimen collecting the infrared radiation from its surface. During 0.06 s the camera creates an image called frame. The frame contains few details, but the short time of its creation can be valuable in monitoring the change of temperature corresponding to the beginning of the process of elongation. Four such frames superimposed over each other create a thermal picture, obtained during 0.24 s. This thermal picture is a basis for analysis of the temperature distributions of the examined surface. Such distributions can be presented in different units depending on the chosen curve of calibration. The mean-square error of temperature evaluation was about 0.2 K. In order to secure higher and more homogeneous emissivity, the surfaces of the samples were blackened with a carbon powder. More details about the used thermovision equipment are given in [16].

The temperature was determined as the average value taken from the surface of the specimen of about 70 mm × 5 mm. An example of thermogram with marked zone of temperature measurement and the calculated value of temperature was shown in Fig. 1.

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3. Changes in the field of temperature during martensite transformation

Mechanical characteristics and numerous thermograms were obtained, which show the temperature distribution on the surface of samples during their deformation. A detailed analysis of thermograms indicate, that the changes of temperature fields measured on the sample surface during its straining at room temperature (295 K) are different than those obtained for higher temperature (333 K). In order to illustrate the differences, the thermograms corresponding to some choosen points of stress-strain curves for both ambient temperatures were made.

For example, in the case of the room temperature test with the strain rate equal to $1.87 \cdot 10^{-3}$ s^{-1}, thermograms at the following values of strain were chosen: 0, 0.01, 0.02, 0.03, and the last one made at the end of unloading. The characteristic points have been marked on the stress-strain curve in Fig. 2 and the obtained thermograms are shown in Fig. 3.

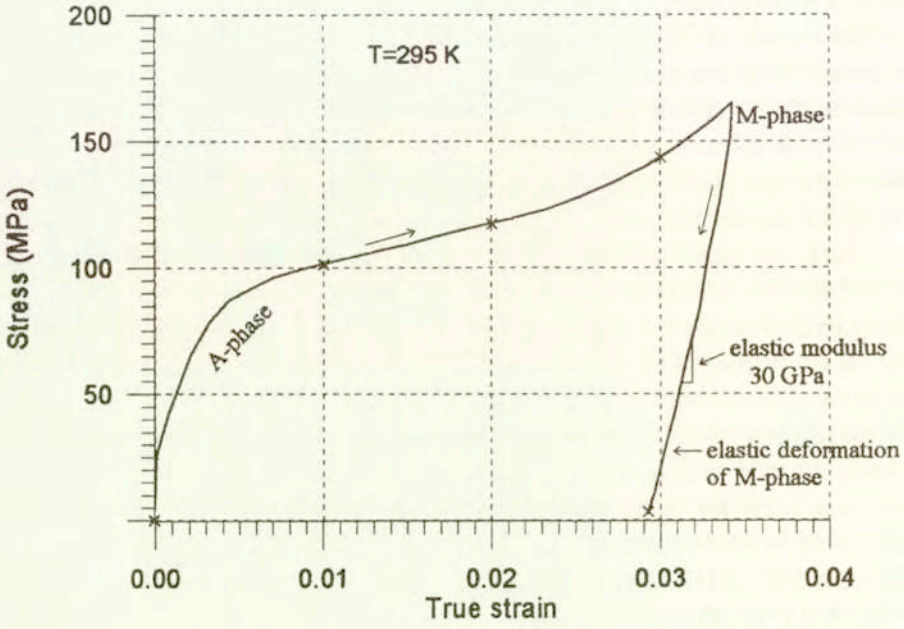

FIG. 1. Stress-strain curve with marked points chosen for analysis of the fields of temperature under room conditions, $\varepsilon = 1.87 \cdot 10^{-3}$ s^{-1}.

It is seen that temperature distribution on the surface of the specimens examined in room temperature was uniform, what indicates the homogeneity of the stress and the strain state along the specimen. In other words, the infrared measurements prove , that the process of nucleation and the growth of martensite proceed homogeneously in the whole volume of the specimen.

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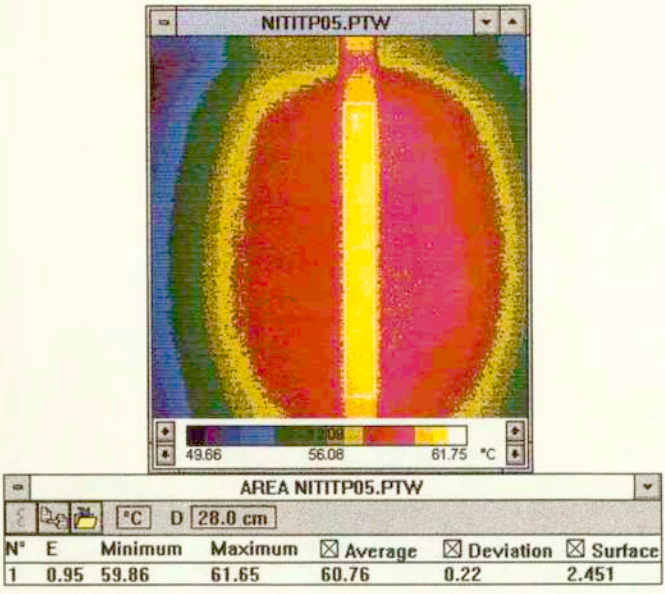
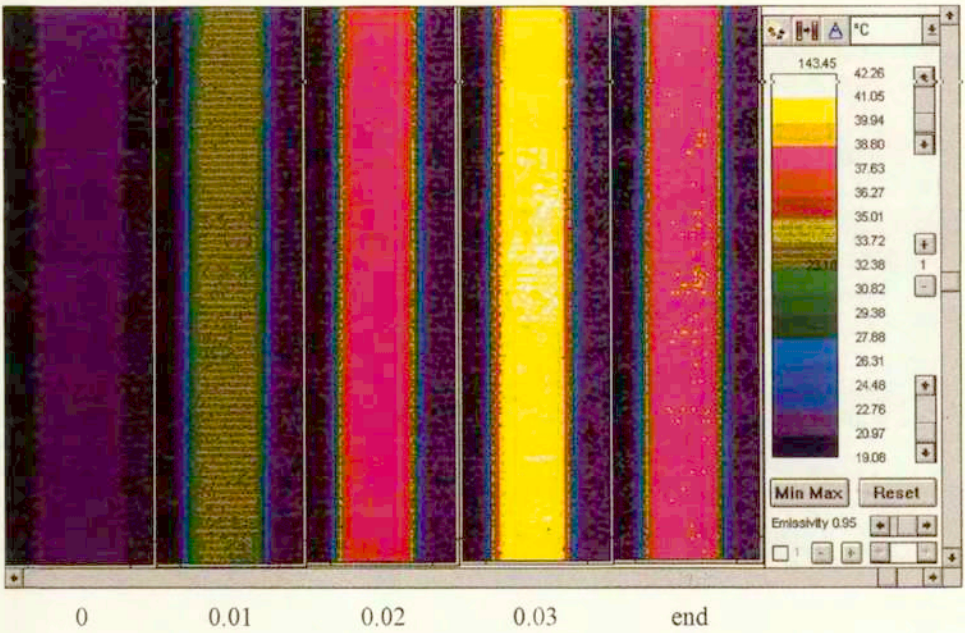


FIG. 2. Example of thermogram with the pointed area of temperature measurement.



0 0.01 0.02 0.03 end

FIG. 3. Temperature distribution on the surface of TiNi specimen subjected to uniaxial loading test at room temperature with the constant strain rate $\dot{\varepsilon} = 1.87 \cdot 10^{-3}$ s^{-1}, obtained after straining: 0, 0.01, 0.02, 0.03, and at the end of unloading.

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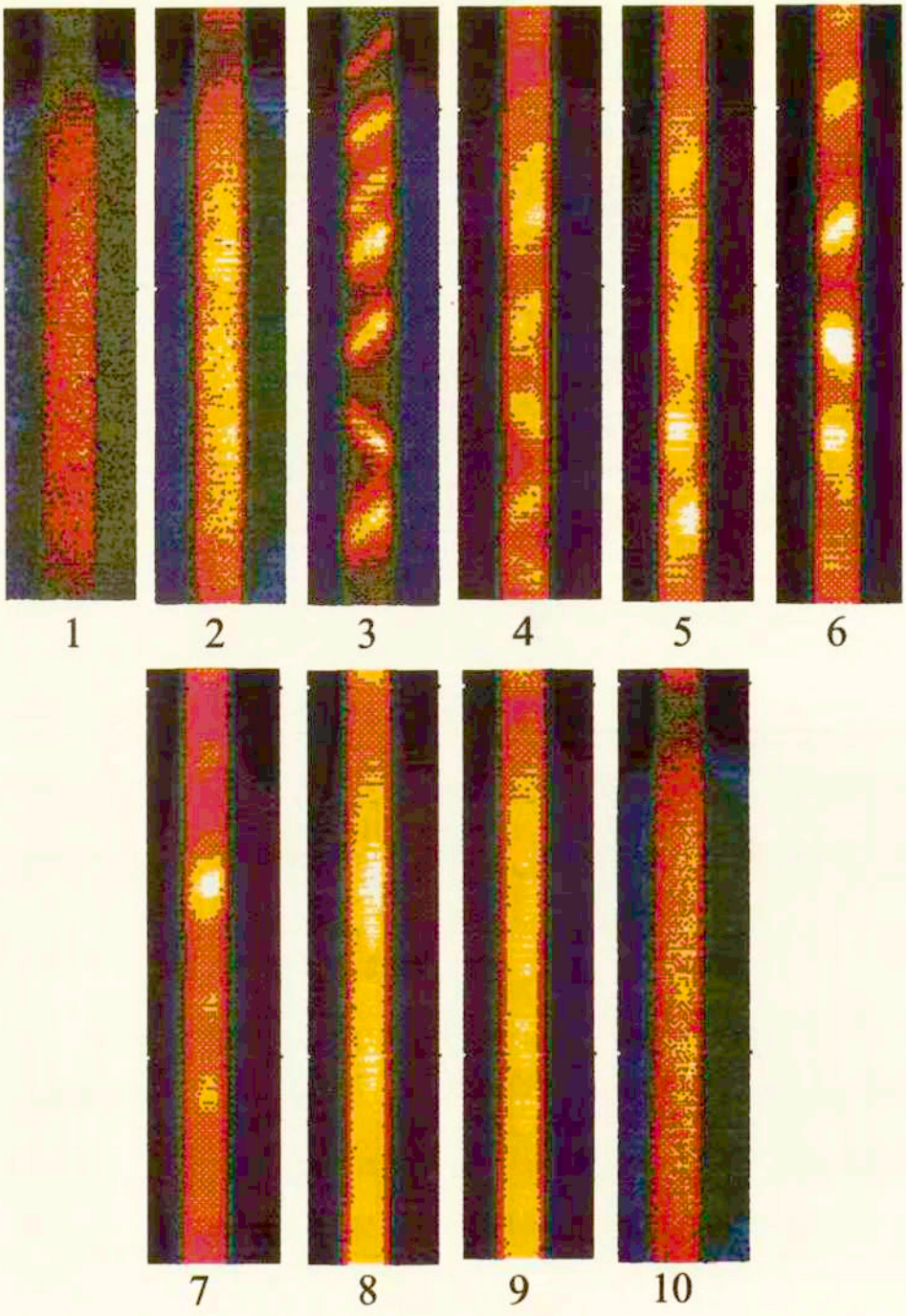

FIG. 5. Temperature distribution on the surface of TiNi specimen subjected to uniaxial loading test at temperature 333 K with the constant strain rate $\dot{\varepsilon} = 1.87 \cdot 10^{-3}$ s^{-1}. Numbers below the thermograms correspond to points at the curve in the Fig. 4.

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In the case of temperature equal to 333 K different results were obtained. The example of the stress-strain curve with marked points which have been chosen for the analysed fields of temperature are shown in Fig. 4 and the corresponding thermograms are presented in Fig. 5. The strain rate was equal to $1.87 \cdot 10^{-3}$ s^{-1}, the same as in the previous example. Black colour in Fig. 5 (minimum of temperature) corresponds to 58°C and is the same in all thermograms. The temperature values of white colour for each thermogram as well as the strain values corresponding to them, are given in Table 1.

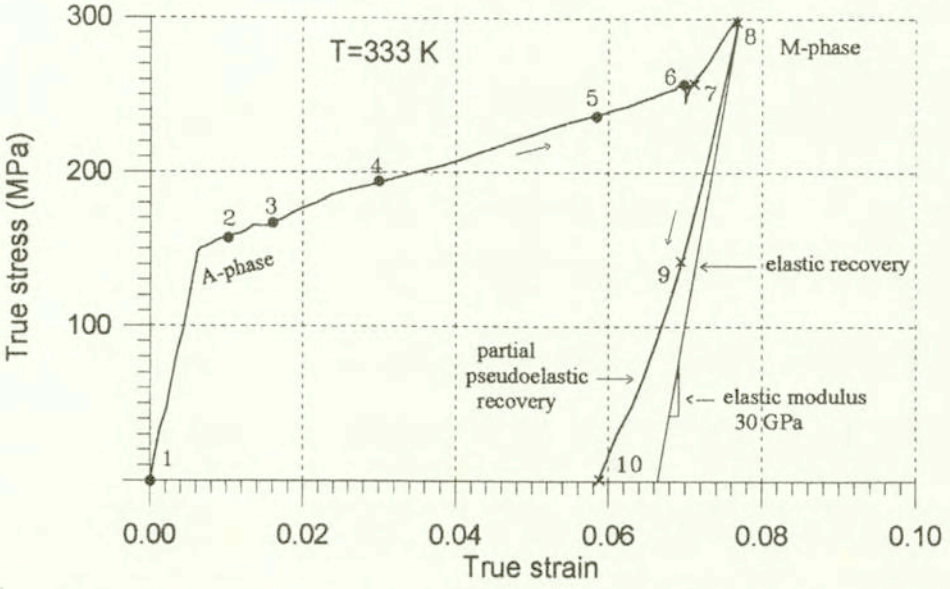

FIG. 4. Stress-strain curve with marked points chosen for analysis of the thermograms at temperature 333 K, $\dot{\varepsilon} = 1.87 \cdot 10^{-3}$ s^{-1}.

Table 1.

No. of thermograms	White colour temperature (°C)	True strain
1	61.06	0.0000
2	62.52	0.0133
3	65.68	0.0153
4	72.88	0.0305
5	79.55	0.0588
6	82.10	0.0695
7	81.70	0.0710
8	78.43	0.0765
9	70.40	0.0697
10	61.94	0.0589

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At the beginning of tension (points 1, 2 in the Fig. 4, 5), the temperature of the sample surface is homogeneous. (Dimension of the silicon window was smaller than that of the used infrared camera objective, so we have taken into account only a part of the sample picture, without the end areas.) Next, at point 3, temperature in the same areas of the sample rapidly increases. These areas are probably regions of creation of the martensite phase. As the strain grows, appearance of these areas changes (points 4, 5, 6); they become not well marked, because the heat flows and the martensitic phase develops. When the martensite transformation is finished (point 7), the differences in the field of temperature decreases. During unloading (points 8, 9, 10) temperature of the sample surface becomes homogeneous again.

FIG. 6. Regions of plastic deformations created during martensite transformation caused by deformation of TiNi shape memory alloy in temperature 333 K.

Creation and next extension of the martensite phase in the same regions of the sample leads to creation of local plastic deformations in the neighbour regions. They have the form of bulges on the surface of the sample (Fig. 6). These regions are caused by the stress concentration occurring during martensite transformation and constrains following from the holding system of the sample [17]. Heating, after which the sample returns to its previous size, does not remove completely the traces of the plastic deformation but only makes them less visible.

4. Thermomechanical coupling during loading and unloading

The mechanical characteristics obtained during the uniaxial tensile test of the samples of TiNi shape memory alloy strained at four strain rates in room temperature are shown in Fig. 7.

After the elastic deformation in the short initial range of loading, yielding – caused by the martensitic transformation – occurs at the stress of $70 \div 90$ MPa. It corresponds to the strain of about 0.005. The intensity of martensitic transformation increases with the strain (caused by loading) and it is followed by a small increase of stress. At the end of martensitic transformation elastic deformation starts again.

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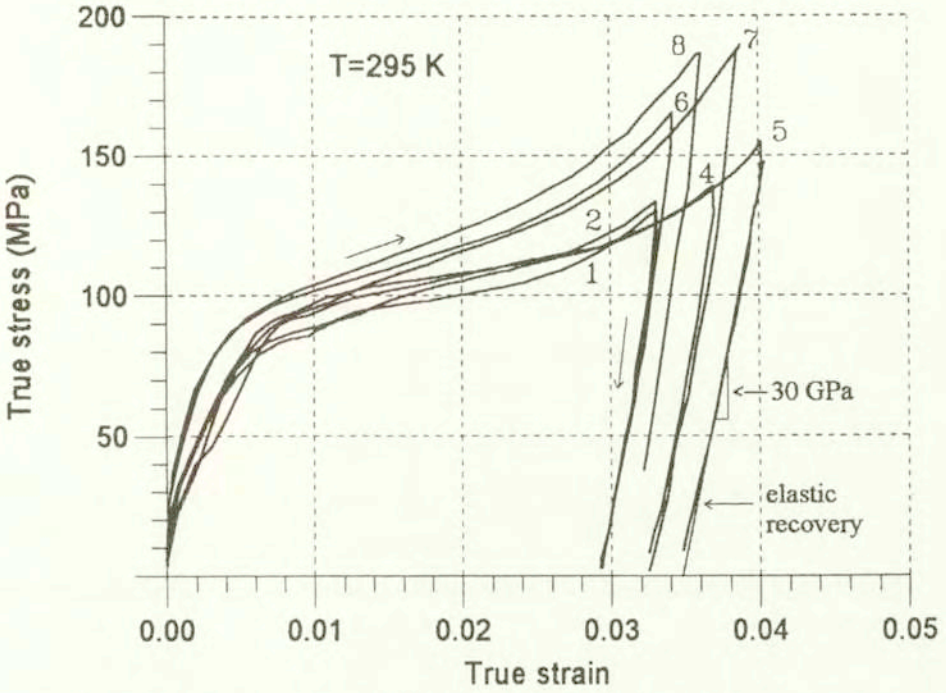

FIG. 7. The stress-strain relation of TiNi shape memory alloy strained at the temperature 295 K with various strain rates: $1, 2 - 0.47 \cdot 10^{-3}$ s^{-1}; $4, 5 - 0.93 \cdot 10^{-3}$ s^{-1}; $6, 7 - 1.87 \cdot 10^{-3}$ s^{-1} and $8 - 4.67 \cdot 10^{-3}$ s^{-1}.

After unloading started from the strain of $0.03 \div 0.04$, the recoverable residual strain of the order of $0.029 \div 0.035$ appears. The starting point of unloading was not the same in all tests. The temperature evolution of the surface of the tested specimens, obtained during their loading and unloading in room temperature at four various rates of deformation, is shown in Fig. 8. One should notice that the thermoelastic effect was not observed here.

The relations $\Delta T(\varepsilon)$ (Fig. 8) point out a visible dependence of temperature on the strain rate, when the differences between the mechanical curves are not so well-marked (Figs. 7 and 8). Changes of the mechanical characteristics obtained for the higher strain rates can be related to the increase of the temperature of the material during these processes, what follows from in the results of the investigations of TiNi shape memory alloys presented in other papers [9].

The mechanical characteristics obtained during the test performed at the temperature 333 K (Fig. 9) are located much higher, i.e. the value of stresses corresponding to martensite transformation is greater: $150 \div 180$ MPa. Range of the strain of this transformation is also higher. The starting points of unloading in each test were not the same, as in the case of room temperature.

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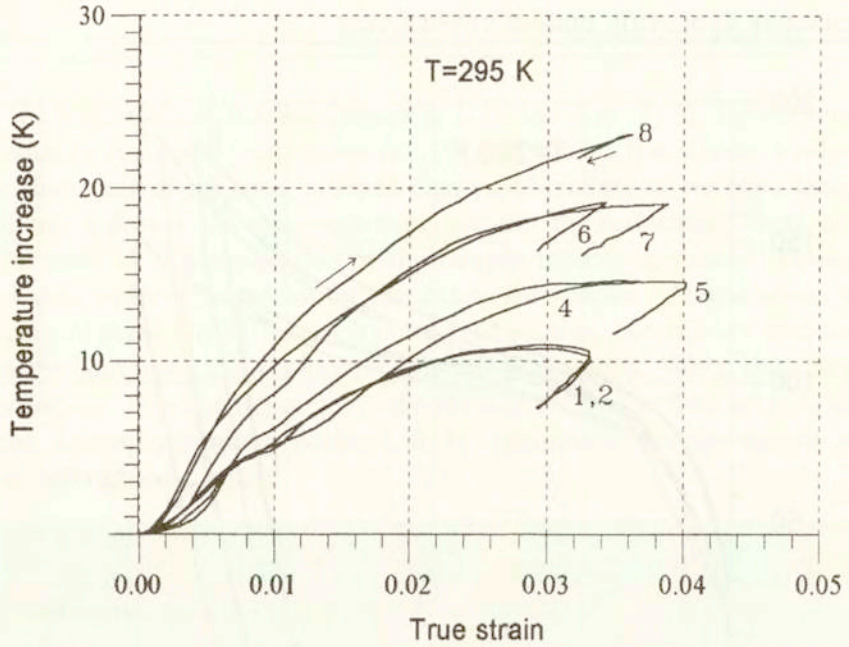

FIG. 8. Changes in temperature of TiNi shape memory alloy strained at the temperature 295 K with various strain rates: $1, 2 - 0.47 \cdot 10^{-3}$ s^{-1}; $4, 5 - 0.93 \cdot 10^{-3}$ s^{-1}; $5, 7 - 1.87 \cdot 10^{-3}$ s^{-1} and $8 - 4.67 \cdot 10^{-3}$ s^{-1}.

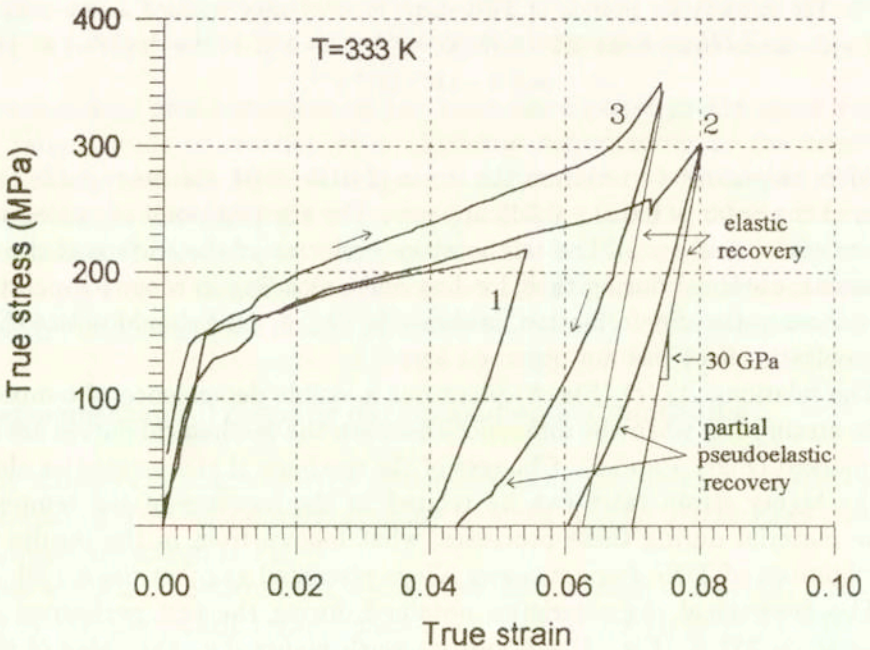

FIG. 9. The stress-strain relation of TiNi shape memory alloy strained at the temperature 333 K with various strain rates: $1 - 0.93 \cdot 10^{-3}$ s^{-1}; $2 - 1.87 \cdot 10^{-3}$ s^{-1} and $3 - 4.67 \cdot 10^{-3}$ s^{-1}.

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The changes in temperature (Fig. 10) corresponding to them are not so smooth as at room temperature, because temperature on the sample surface is not homogeneous in the region of martensitic transformation. The increments of temperature are higher and the decrements measured during unloading are higher too.

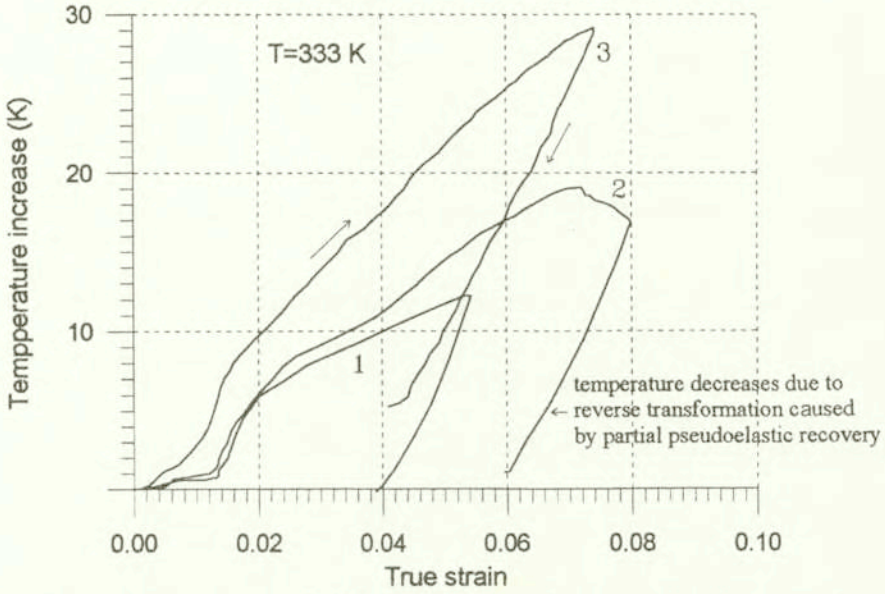

FIG. 10. Changes in temperature of TiNi shape memory alloy strained at the temperature 333 K with various strain rates: $1 - 0.93 \cdot 10^{-3}$ s^{-1}; $2 - 1.87 \cdot 10^{-3}$ s^{-1} and $3 - 4.67 \cdot 10^{-3}$ s^{-1}.

Especially interesting results of the experiments carried out are the temperature changes obtained for various strain rates and described as a function of stress. The results obtained for temperature 295 K are presented in the Fig. 11, and those for elevated temperature (333 K) in the Fig. 12.

Temperature distribution on the sample surface deformed at room temperature was homogeneous, so mean square error of the temperature was the same and equal to 0.2 K. At elevated temperature this distribution was not homogeneous. The mean square error of its measurement was different and is shown in the Fig. 12.

It was found, that the temperature changes during loading plotted as a function of stress, are similar for all of the applied strain rates. The relations between the temperature changes and the stress registered in the range of martensitic transformation are independent of the strain rate. One can conclude that the stress related to the temperature increments induces the martensitic transformation independently of the path and time of deformation. The relation $\Delta T(\sigma)$ can be regarded as the intrinsic characteristic of the tested shape memory alloy.

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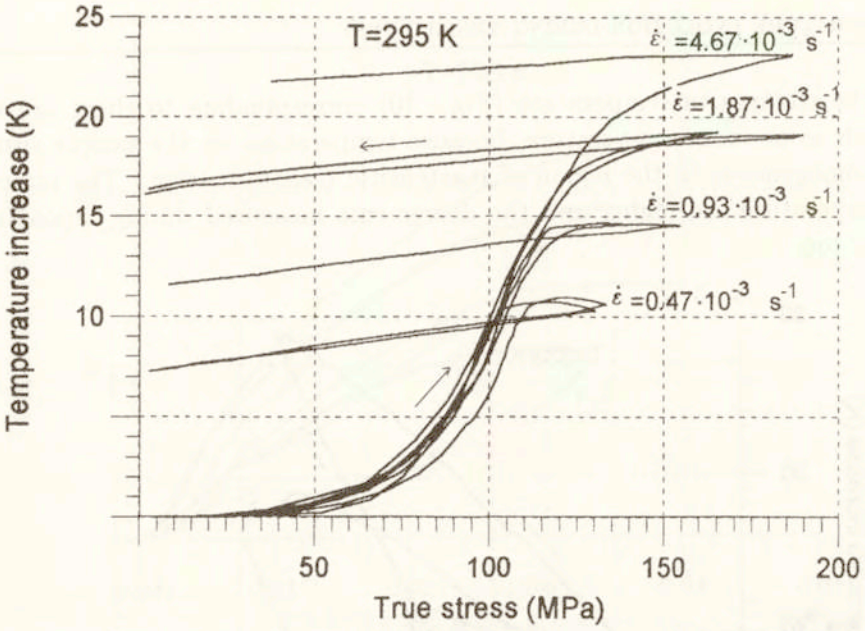

FIG. 11. Stress dependence of temperature change for various strain rates of TiNi shape memory alloy loaded at the temperature of 295 K.

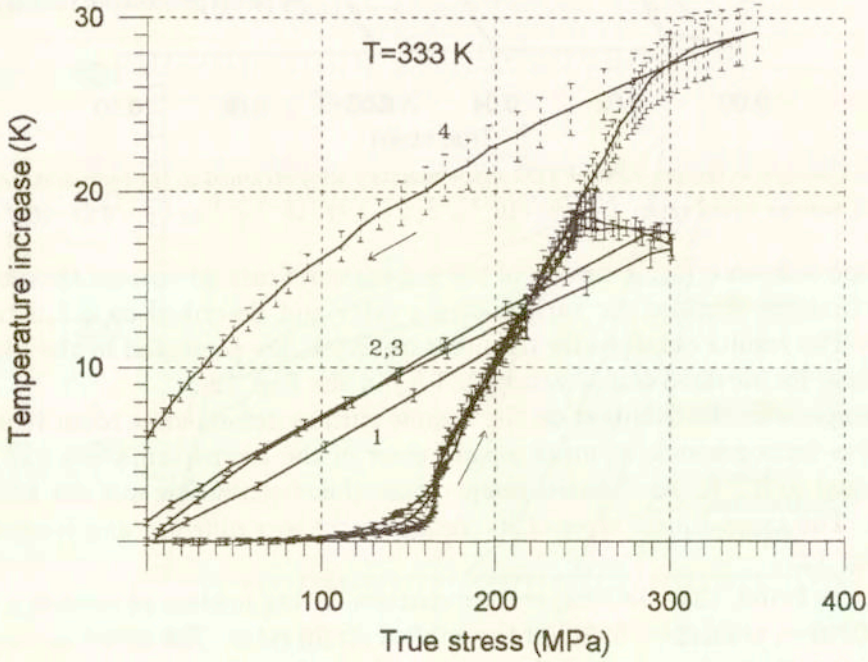

FIG. 12. The increase of temperature-strain relation of TiNi shape memory alloy loaded at the temperature of 333 K with various strain rates: $1 - 0.93 \cdot 10^{-3}$ s^{-1}; $2,3 - 1.87 \cdot 10^{-3}$ s^{-1} and $4 - 4.67 \cdot 10^{-3}$ s^{-1}.

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During unloading of the specimen at room temperature, the curves $\Delta T(\sigma)$ are parallel to each other (Fig. 11). Temperature decreases by about 1 – 2 K for every test. The process of cooling was independent of the strain rate, what means that disturbances related to the differences in the heat transfer to the surrounding (for various rates of deformation) are negligible.

For tests carried out at temperature 333 K, changes of temperature obtained during unloading are much larger – reaching 20 K (Fig. 12). Such a high temperature changes are caused by the reverse transformation. As seen in Figs. 2 and 7, the unloading curves are linear and elastic modulus of the martensitic phase is 30 MPa. On the other hand, as seen in Figs. 4 and 9, the unloading curves are nonlinear and partial pseudoelastic recovery is observed. Therefore, in the case of 333 K, partial pseudoelastic deformation appears during unloading and temperature decreases due to the reverse transformation.

5. Conclusions

The temperature distribution measured on the surface of the SMA samples loaded at room temperature (295 K) was uniform, what indicates the homogeneity of the phase transformation process.

Bands of relatively higher temperature increment were observed on the surface of samples loaded at temperature equal to 333 K. The effect of nonhomogeneity was observed during pseudoelastic flow of the sample. It can be concluded that the development of the inartensitic transformation is nonhomogeneous. Before and after the martensitic transformation, the temperature distribution on samples' surface is homogeneous. Both nucleation and the following extension of the martensitic phase in the same regions are accompanied by local plastic deformation in the neighbour regions of the sample. Heating, during which the sample returns to its previous size, does not remove completely the traces of the plastic deformation but only makes them less clearly observable.

The stresses and temperature increases were much higher during the study at temperature 333 K than that at the room temperature. Mechanical characteristics of the tested samples and changes in temperature increase with the strain rate.

The temperature increments presented as a function of stress in the range of the martensitic transformation, for the test carried out in the same conditions, turned out to lie on the same curve, independently of the strain rate. It seems that the relation $\mathrm{DT}(\sigma)$ is a characteristic of the tested shape memory alloy.

The parallelism of $\Delta T(\sigma)$ characteristics during unloading of the samples tested at room temperature indicates that the decrease of temperature was caused only by heat of energy dissipation. Decrease of temperature during unloading of

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the samples tested in ambient temperature of 333 K was much higher and was caused by reverse transformation accompanied by partial pseudoelastic recovery.

Acknowledgments

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