PAPER REF: 2921

TEMPERATURE ASSESSMENT OF TiNi SHAPE MEMORY ALLOY SUBJECTED TO COMPRESSION AT QUASISTATIC AND DYNAMIC STRAIN RATES

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ABSTRACT

This work compares the thermomechanical behavior of TiNi shape memory alloy subjected to the compression test performed under various strain rates. The mechanical characteristics of the material were elaborated. The specimen temperature changes related to the exothermic martensitic forward and endothermic reverse transformation were measured in a contact-less manner by a very fast and sensitive infrared camera. It has been found that in this experimental conditions the stress-induced transformation and reorientation processes occurred homogeneously, since the temperature distribution observed on the specimen surface was uniform. The obtained temperature variation depends on the strain rate applied. At the higher strain rate the higher temperature changes were obtained, because the heat flow to the surroundings was lower and the process was closer to adiabatic conditions. The temperature changes influence significantly the SMA stress-strain curves and their mechanical properties.

INTRODUCTION

Shape memory alloys (SMA) are strongly temperature-dependent and their further development depends on our knowledge on their thermomechanical properties manifested in various loading conditions. The main phenomena which appear in a SMA, depending on the test temperature T and enabling various applications, are shape memory effect (SME) and superelasticity (SE). They are controlled by two material parameters: the austenite finish (A_f) and the austenite start (A_s) temperatures. If $T>A_f$, the SE appears, and if $T<A_s$, it is SME that prevails. The SE behavior is caused by stress-induced reversible martensitic transformation (SIMT) taking place during the SMA loading and unloading. In this case, almost complete reverse transformation occurs during the unloading. In the case of SME, caused mainly by the structure reorientation that occurs during the loading, quite a significant residual strain is observed after the SMA unloading. The residual strain disappears, if the SMA is heated after the unloading above the A_f temperature. Superelastic properties and stress-induced transformation bands were studied in TiNi SMA under static tension or shear, performed with various strain rates, e.g. Pieczyska *et al.* [1,2], and dynamic tension, Nemat-Naser *et al.* [3]. There are also some studies on TiNi compression, however the accompanying temperature changes were seldom taken into account. In this research, both mechanical and temperature characteristics were investigated under compression in wide spectra of strain rates. The test was performed in vicinity of the A_f temperature, so a mix of the SE and SME was observed. The temperature distribution on the specimen surface and the temperature variation accompanying the SMA loading and unloading were determined. An influence of the strain rate and its related temperature changes on the SMA thermomechanical behavior is discussed.

EXPERIMENTAL DETAILS

The TiNi shape memory alloy used in this research was produced by the *Furukawa Electric Co*. The quasistatic compression tests have been carried out on *Instron* testing machine using small bar specimens of ϕ 5 mm and 7.5 mm length (2.5 mm in case of impact test). During a preliminary test, a laser extensometer was used to measure strain independently of the mechanical extensometer coupled to the testing machine (Fig. 2). This test allowed us to validate the measuring system applied. Each test on the testing machine was controlled by the mechanical extensometer. The true stress - true strain characteristics were elaborated. The temperature changes of the specimen were recorded in a contact-less manner using a fast and sensitive infrared camera *Phoenix, Flir Co.* On the basis of the stress-strain curves and temperature changes related to them, the effects of thermomechanical coupling were studied. Taking into account the temperature distribution on the specimen surface, the nucleation and development of the stress-induced martensitic transformation have been examined.

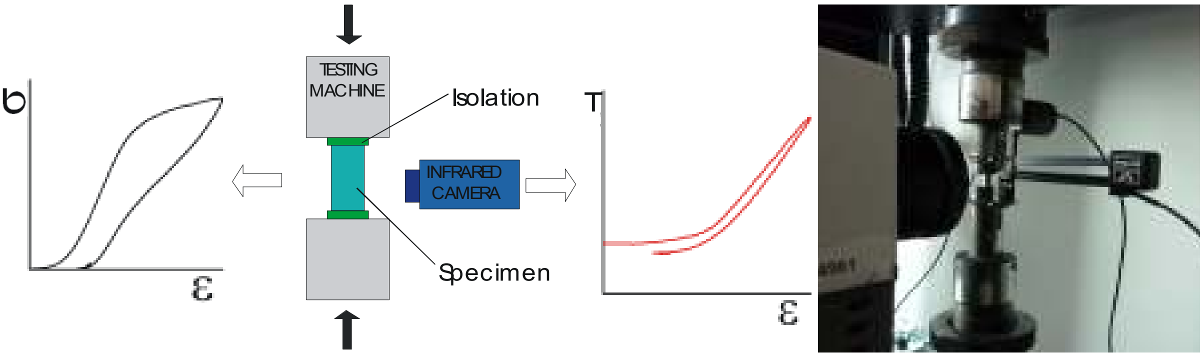

Fig.1 Scheme and photography of the experimental setup

STRESS-STRAIN AND TEMPERATURE CHARACTERISTICS

The loading measurement system was checked up during the initial test, with the help of the laser extensometer, measuring the strain data independently of the testing machine. The results obtained for strain rate $10^{-3}s^{-1}$ are shown in Fig. 2.

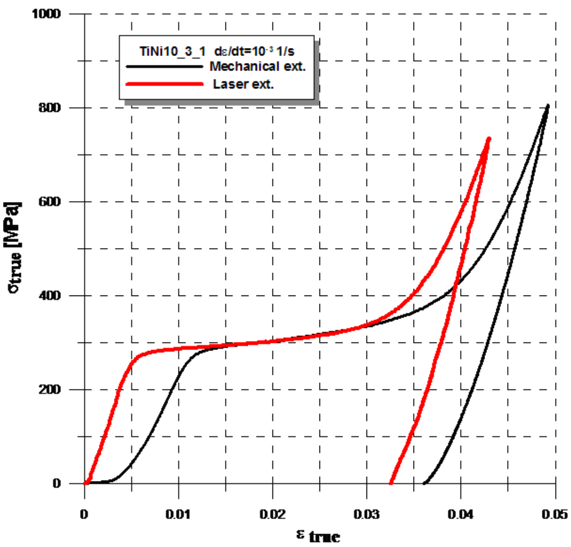

Fig.2 Comparison of stress vs. strain curves obtained for TiNi SMA during compression with strain rate $10^{-3}s^{-1}$ by mechanical and laser extensometers

It should be noticed that the Young modulus recorded by the laser extensometer is higher, however the strain range related to the forward transformation (reorientation) is similar to that obtained by the mechanical extensometer. The laser extensometer cannot be used during the following tests, carried out with thermovision camera, since it perturbs the infrared measurements. Furthermore, the mechanical extensometer was used in this approach to control the testing machine and assure the required compression test parameters.
The martensitic forward transformation developing in SMA is exothermic and the reverse one is endothermic [1]. The mechanical characteristics accompanied by the average temperature variation of the specimen obtained for strain rate $10^{-3}s^{-1}$ are presented in Fig. 3. According to the SMA DSC results, the test was performed in the vicinity of the A_f temperature (296 K), so a mix of the SE and SME was observed during the SMA compression at room temperature in the range of 292 K - 295 K.

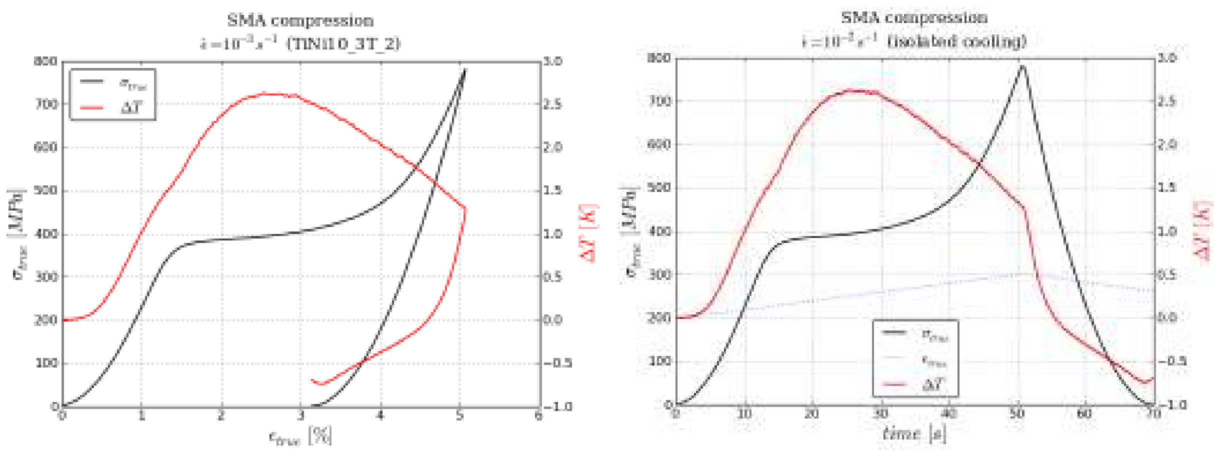

Fig.3 Stress and temperature variation vs. strain and time curves obtained for TiNi SMA during compression with strain rate $10^{-3}s^{-1}$

The SMA temperature starts raising at the strain of approximately 0.2%, increasing up to 2.6 K at a strain of 2.5%. At higher strain a decrease in temperature is observed proving that the heat flow to the surroundings is higher at this compression stage than the heat production related to the exothermic forward transformation for the strain rate applied. During the unloading a much significant temperature decrease is observed related to the endothermic reverse transformation. The stress-strain profile recorded during unloading manifests a contribution of the SMA superelasticity, whereas a significant residual strain recorded after the specimen unloading is linked to the shape memory effect.
At higher strain rates equal to $10^{-2}s^{-1}$, the temperature variation related to the phase transformation is much higher (up to 17K) which influences significantly the stress-strain profile (Fig. 4). Namely, the slope of the stress-strain curve during the loading is steeper and the residual strain recorded after the SMA unloading is lower. The effects are even more explicit at strain rate $5x10^{-2}s^{-1}$, while the temperature variation up to 30 K and the residual strain of only 1.2 % were recorded (Fig. 5).

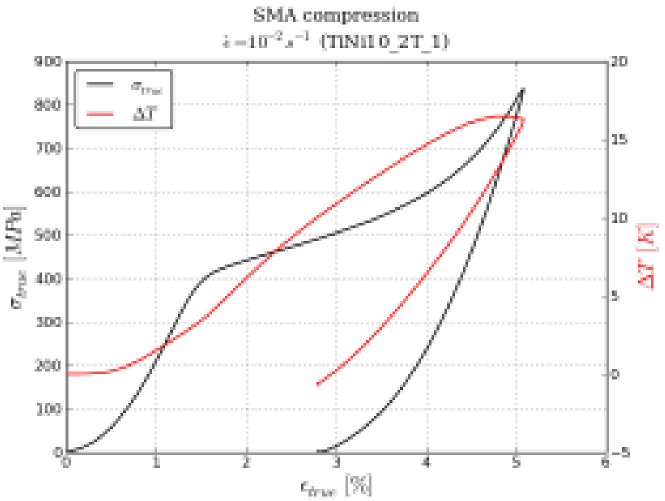

Fig.4 Stress and temperature variation vs. strain curves obtained for TiNi SMA during compression with strain rate $10^{-2}s^{-1}$

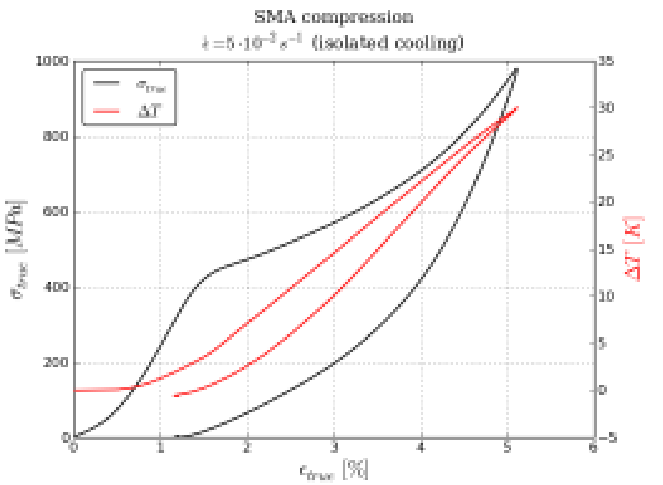

Fig.5 Stress and temperature variation vs. strain curves obtained for TiNi SMA during compression with strain rate $5x10^{-2}s^{-1}$

One can notice comparing the stress and temperature vs. strain curves obtained for various strain rates that at higher strain rates the recorded temperature changes are caused mainly by the martensitic transformation. For this reason they are more related to the stress profile. At higher strain rates and related greater temperature changes the both forward and reverse transformation occurs at higher stress level, therefore the recorded hysteresis loops are narrower. We can notice a similar tendency related to temperature curves.

DYNAMIC COMPRESSION TEST

The results of dynamic compression test, carried out on TiNi SMA using the Split Hopkinson Pressure Bar (SHPB) method are shown in Fig. 6. It presents data obtained for three subsequent cycles of loading with the strain rate equal to $10^{3}s^{-1}$, approximately. Various stages of deformation can be distinguished on the stress-strain curve, i.e.: elastic deformation of the parent austenite phase, transition into martensite and reorientation started at about 430 MPa and developing up to 620 MPa, elastic deformation of the new phase followed by its plastic flow. The maximal stress attained is up to 1800 MPa. During the unloading, after the elastic stage the shape memory properties are noticed.

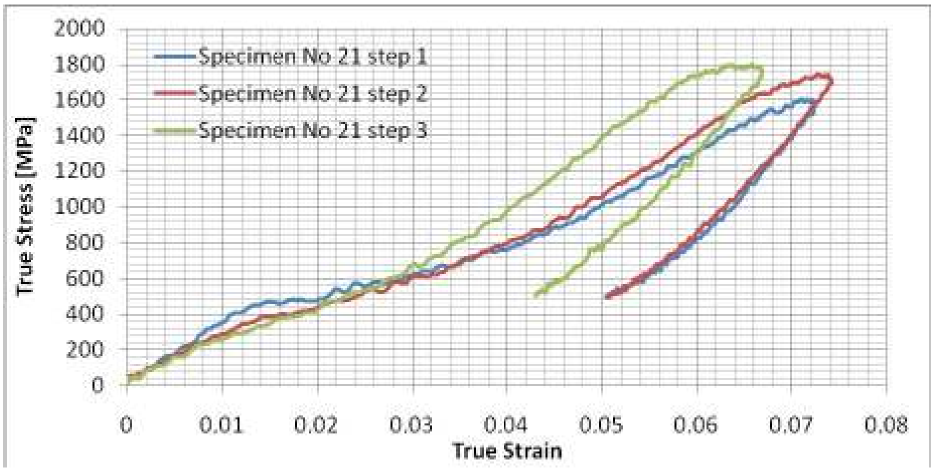

Fig. 6 Dynamic compression test results for three subsequent deformation cycles of TiNi SMA performed using Split Hopkinson Pressure Bar at strain rate equal to $10^3 s^{-1}$

DISCUSSION

The stress-strain characteristics obtained at various strain rates in quasistatic strain rate range shown in Figs. 3-5 are presented in the same diagram in Fig. 7. In addition, the stress-strain data for the lower strain rate $10^{-4}s^{-1}$ and higher strain rate $10^{-1}s^{-1}$ are given.

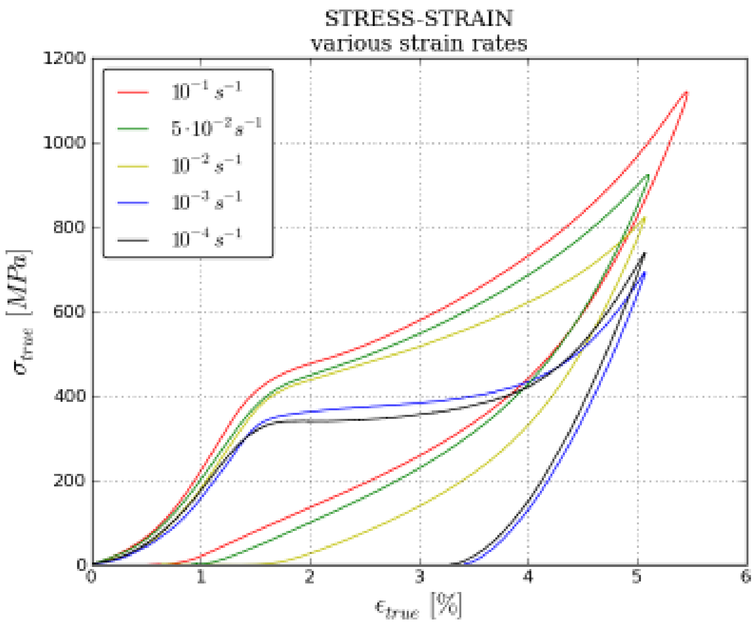

Fig.7 Stress vs. strain curves obtained for TiNi SMA during compression for various strain rates ($10^{-4}s^{-1}$, $10^{-3}s^{-1}$, $10^{-2}s^{-1}$, $5x10^{-2}s^{-1}$, $10^{-1}s^{-1}$)

One can notice looking at Fig. 7 that:

- no major discrepancies are observed in the elastic strain range (except strain rate $10^{-4}s^{-1}$)
- the higher strain rate, the higher temperature which follows the higher stress of the SMA yielding related to the phase transformation
- the higher strain rate, the higher SMA temperature and thus the higher shape recovery
- the higher strain rate, the higher maximal stress is observed at the strain range applied.

The SMA behavior manifested at various strain rate can be explained in the following way. Both the forward transformation and the reverse transformation stress in SMAs increase in proportion to the temperature. Therefore, in general, the shape memory effect is observed at low temperature (below M_S, here 294 K), the partial superelasticity at higher temperature and the perfect superelasticity above A_f temperature. It is also well known that the residual strain recorded after SMAs unloading can be removed during the further alloy heating at the temperature above A_f. During the compression performed at high strain rates, the SMA specimen attained high temperature due to the exothermic transformation and the test was close to adiabatic conditions. If strain rate is high, the temperature rise is large, resulting in an increase in the reverse transformation stress. The reverse transformation behavior is affected due to the temperature rise that occurs during the forward transformation. The dependence of the deformation behavior on temperature must appear in the compression test depending on the temperature rise due to dependence on strain rate. In this way at the strain rate $10^{-1}s^{-1}$ the hysteresis loop is narrow and almost total shape recovery is observed. The comparison of the mechanical and temperature results obtained during the TiNi SMA compression for the quasistatic and dynamic strain rates are shown in Table 1.

Table 1

Stress/strain rate	$10^{-4}s^{-1}$	$10^{-3}s^{-1}$	$10^{-2}s^{-1}$	$5 \times 10^{-2}s^{-1}$	$10^{-1}s^{-1}$	$10^{3}s^{-1}$
Stress of SIMT yield [MPa]	340	380	415	420	430	430
Maximal stress [MPa]	640	780	860	870	1140	1800
Max. average temp. inc. [K]	0.50	2.65	17	30	37	?
Residual strain after unl. [%]	3.3	3.4	1.5	0.9	0.7	?

CONCLUSIONS

This study shows significant differences between the thermomechanical behaviors of the TiNi shape memory alloy subjected to compression with various strain rates. These differences are caused by the latent heat that accompany the SMA loading and causes an increase of the specimen temperature. At low strain rate, the heat flows to the specimen grips and surroundings. At higher strain rate the process is closer to adiabatic conditions and the higher increase of the specimen temperature is recorded. The higher temperature increase causes the higher stress during the SMA loading and the higher shape recovery during the unloading. Moreover, a strong regularity in stress-strain curves is observed as the strain rate increases.

ACKNOWLEDGMENTS

The authors acknowledge the Polish Ministry of Science and Higher Education; Grant 501220837, the National Center of Science: Grant 2011/01/M/ST8/07754. The infrared measurements were performed by M.Maj to whom the authors wish to express their gratitude.

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