SHAPE MEMORY ALLOY UNDER STRAIN- AND STRESS-CONTROLLED CONDITIONS – THERMOMECHANICAL ASPECTS OF THE MARTENSITE AND REVERSE TRANSFORMATIONS

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Summary Thermomechanical aspects of martensite and reverse transformations in TiNi shape-memory alloy subjected to strain and stress control were investigated. The temperature distributions on the specimen's surface were determined by using an infrared camera. The results differ in mechanical behavior, however at both approaches, heterogeneous temperature distributions, related to the nucleation and development of the new phase, were observed. The similar heterogeneous effects were observed during unloading, while the reverse transformation took place, accompanied by significant temperature decrease.

Shape memory alloys (SMAs) are interesting group of modern materials with the feature to remember a shape after a significant deformation, up to 8%, recovered by an increase in temperature (shape memory effect) or large nonlinear elastic range (pseudoelasticity). These characteristics as well as significant internal damping and high yield stress enable them using in advanced and smart structures [1, 2]. Most popular and widely applied to practical use is TiNi SMA, due to its superior memory, structure properties and excellent corrosion resistance. The objective of our work is to provide accurate experimental data of a TiNi shape memory alloy in order to study of thermomechanics of nucleation and further development of stress induced martensite transformation. To this end, stress and strain controlled tensile tests were performed with various rates of deformation. A thermovision camera was used in order to register the distribution of infrared radiation and calculate the temperature changes of the TiNi specimens subjected to loading. The infrared camera is very useful in such research, since it enables to identify the area of higher or lower temperature, related to occurrence of the new material phase. The obtained temperature images were stored for further analysis; such approach enabled to observe, register and analyze the kinetics and thermodynamics of the phase transitions.
The sheet specimens of 160 x 10 x 0.4 were cut off from the band of SMA. Each specimen was covered by carbon powder in order to obtain a higher and homogeneous emissivity. The specimens were subjected to the strain controlled tensile test with the strain rates 5 x $10^{-3}s^{-1}$, $10^{-2}s^{-1}$, 5 x $10^{-2}s^{-1}$, and the stress controlled tensile test with the stress rates 12.5 MPa s^{-1}, 25 MPa s^{-1}, 50 MPa s^{-1}, 75 MPa s^{-1}. The temperature changes were calculated as an average from the specimen area ≈ 400 mm^2. The examples of obtained characteristics are shown in Fig.1a and Fig.1b. Taking advantages from the infrared camera, it was observed that just after the uniform temperature distribution registered in the elastic range, the temperature slightly increased in the central area of the sample which was followed by the sudden occurrence of the first inclined line of significantly higher temperature (Fig.2a), probably related to the nucleation of the new, martensite phase. After a while, a few such lines parallel to each other occurred and moved towards the sample borders, as well as the next "family" of them, developing in the perpendicular direction (Fig.2b). At higher strain, the regions of higher temperature became less clearly defined (Fig.2c), most likely because of the further martensite phase development in the whole material volume and the heat flow. When the martensitic transformation was completed, the temperature of the specimen surface became almost homogeneous again. The heterogeneous field of temperature distribution has been observed also during unloading of the TiNi, when the reverse transformation took place (Fig.2d), although it was surprising in comparison to the previously obtained results for slightly different kind of TiNi SMA [3].

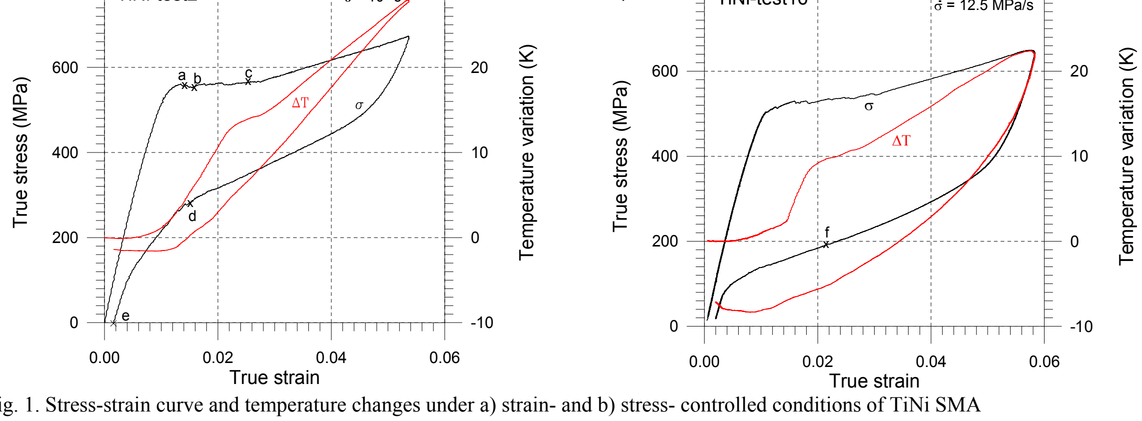

Fig. 1. Stress-strain curve and temperature changes under a) strain- and b) stress- controlled conditions of TiNi SMA

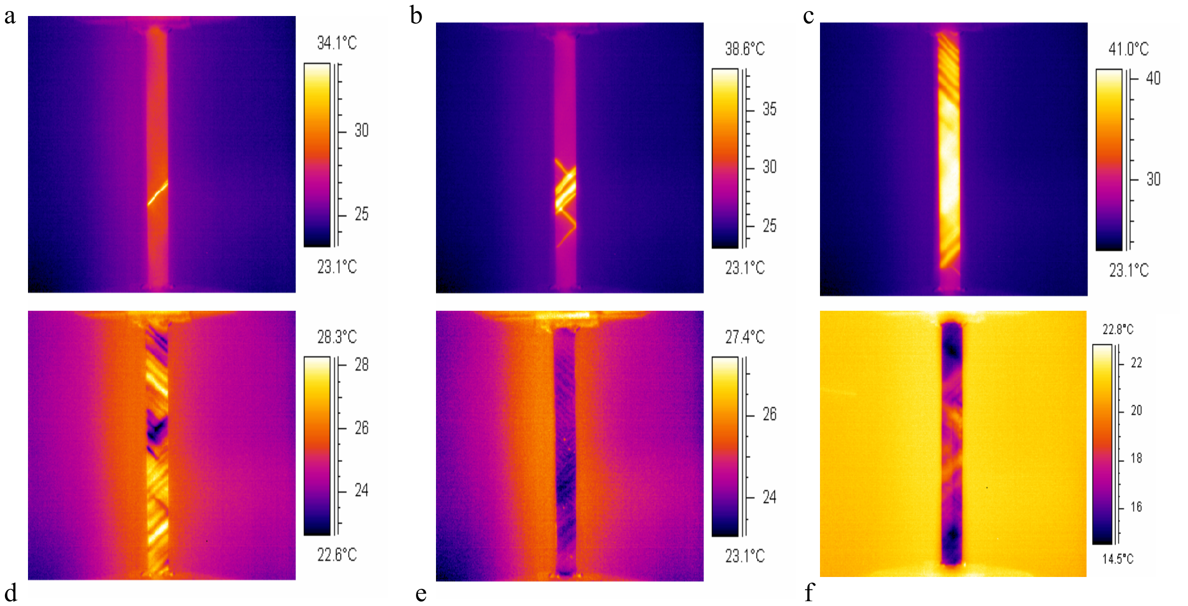

Fig. 2. Temperature distribution of TiNi subjected to uniaxial tensile test at room temperature: The letters correspond to the proper points of the stress-strain curves shown in Fig.1: a, b, c – during martensite transformation, d – during reverse transformation, e – after unloading; f – final part of the stress controlled tensile test.

CONCLUSIONS

The thermomechanical behavior of SMA reflects the exothermic character of the austenite into martensite transformation and endothermic character of the reverse one. The higher the strain rate, the higher the stress of the martensite transformation due to the significant temperature increase and the higher decrease of the transformation stress, caused by the larger decrease in temperature [1]. The sufficiently high rates of deformation applied caused significant temperature changes, which influence on the mechanical characteristics. Such effects of the thermomechanical couplings are noticed in Figs.1a and 1b. The maximal increase in temperature, related to martensitic transformation, was quite significant, up to 30 K in some area: the higher temperature was measured at the cross-section of the interphase bands (Fig.2b). During the unloading, when the reverse transformation (martensite into austenite) took place, the temperature of the specimen in some area falls down with the drop up to 10 K: the lower temperature was measured at the cross-section of the interphase bands (Fig.2d). Particularly interesting were the results obtained after unloading of the strain-controlled test. Namely, after 3.26 s of the unloading to null, the temperature distribution remained still heterogeneous (Fig.2e). It can be explained like this. After unloading, some residual martensite remains. That is, though the reverse transformation completes macroscopically, it does not microscopically complete. Based on this residual martensite, there appears residual or internal stress after unloading. Therefore, some local microscopic reverse transformation still occurs in the elastic region of unloading after the macroscopic finish point of the reverse transformation. Due to this effect, the heterogeneous temperature distribution may appear after unloading. It will be cleared up in research related to cycling tests. The similar effects of heterogeneity accompanied the stress-controlled tests. It means that after a nucleation, the mechanism of the phase transition is the same and does not depend on the stress level. However, the development of the both martensite and austenite transitions took place not exactly the same way. Namely, the temperature distributions observed during the stress-controlled test were more uniform and the changes were smoother. Furthermore, at the end of the stress-controlled test (Fig.1b), significant temperature decrease has been observed, particularly in the grips area (Fig.2f).

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