Abstracts

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＜Keynote Speech＞

My experience with Ti-Ni Shape Memory/Ti-based Superelastic Alloys & Shape Memory Polymers in collaboration with Japanese Researchers

Prof. Elżbieta Alicja Pieczyska, D.Sc. ; JSPS Post-Doc 2004-2006

Institute of Fundamental Technological Research, Polish Academy of Sciences IPPT PAN

Introduction. The new multifunctional solid materials; i.e. TiNi Shape Memory Alloys (SMA), Shape Memory Polymers (SMP) and Ti-Nb Ni free high elastic alloys, named Gum Metals have been investigated using traditional and innovative experimental techniques.

Research on Shape Memory Alloys has been developed at the IPPT PAN from the beginning of 90's of the XX c. by B. Raniecki in cooperation with K. Tanaka (Japan) and C. Lexcellent (France) who proposed some thermodynamic theory of the stress- or temperature - induced phase transformation developing in SMAs [1].

In order to obtain data necessary for verification of the proposed model, various kinds of experiments on TiNi SMAs subjected to uniaxial and complex loading, coordinated by W.K Nowacki and L. Dietrich were conducted at the IPPT PAN in collaboration with Japanese researchers (S. Miyazaki, K. Tanaka and H. Tobushi) [2]. Experimental investigation of effects of thermomechanical couplings in TiNi SMA were started by E.A. Pieczyska, W.K. Nowacki, S.P. Gadaj (IPPT, Poland), and H. Tobushi (AIT, Japan) [3, 4] following and developing an experimental idea of J. Shaw and S. Kyriakides [5]. Furthermore, the SMA micromechanics behaviour have been theoretically analysed by H. Petryk & S. Stupkiewicz [6].

Experimental details and results. The samples of SMA produced by Furukawa, Polyurethane Shape Memory Polymers PU-SMP obtained by SMP Technol. Inc., Tokyo and Gum Metal samples provided by the *Toyota Central Research & Development Labs* - were subjected to loading on Instron Testing Machine. The fast and sensitive Infrared Camera Phoenix Flir Co. was used to collect infrared radiation from the materials sample's surface and to evaluate the temperature change during the loading and deformation process. The mechanical data were elaborated using digital image correlation (DIC) with its own algorithm. Acoustic emission technique (AE) was also used in some approaches. The effects of thermomechanical couplings obtained, applied in the designed system named ThermoCorr and related to the materials structure - allowed us to investigate the new materials behavior in various conditions.

Infrared imaging demonstrating 2 directions of the localised stress-induced phase transformation of the TiNi SMA specimen for strain rate $10^{-2}s^{-1}$ are presented in Fig. 1. Stress induced martensite transformation in the SMA starts before the stress knee homogeneously and develop in transformation bands, which number significantly depend on the strain rate applied.

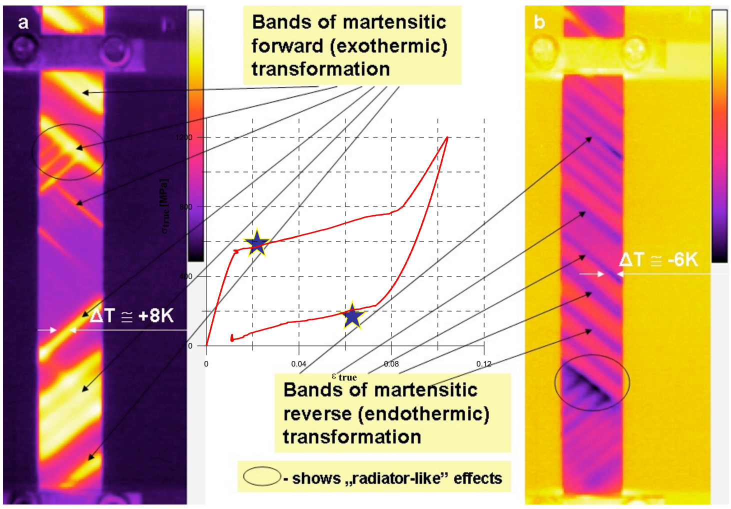

Fig. 1 Infrared imaging demonstrating 2 directions of the localized stress-induced transformation [4]

Investigation of unconventional deformation mechanisms in an innovative Ti-Nb-based alloy named Gum Metal by analysis of the effects of thermomechanical couplings (interactions between mechanical and thermal fields) of the alloy under selected loadings were conducted. The research was motivated by a getting a better understanding of nature of Gum Metal, which simultaneously offers a set of superior mechanical characteristics including low Young's modulus, large range of nonlinear recoverable deformation and high strength. Gum Metal can therefore be successfully used in many fields including the automotive, precision, robotic and sports equipment industries. In addition, the absence of toxic elements in the composition of Gum Metal, its high biocompatibility and low Young's modulus value, closer to bone than that of conventional Ti-alloys, make it a promising candidate for biomedical applications including endodontic instruments and spinal implant systems. The research was realized in collaboration with scientific institutions from Japan including *Toyota Central Research & Development Labs and Fukuoka University,* which provided IPPT with Gum Metal specimens as well as *University of Tsukuba* and *Ibaraki University*, which gave scientific support and important advice.

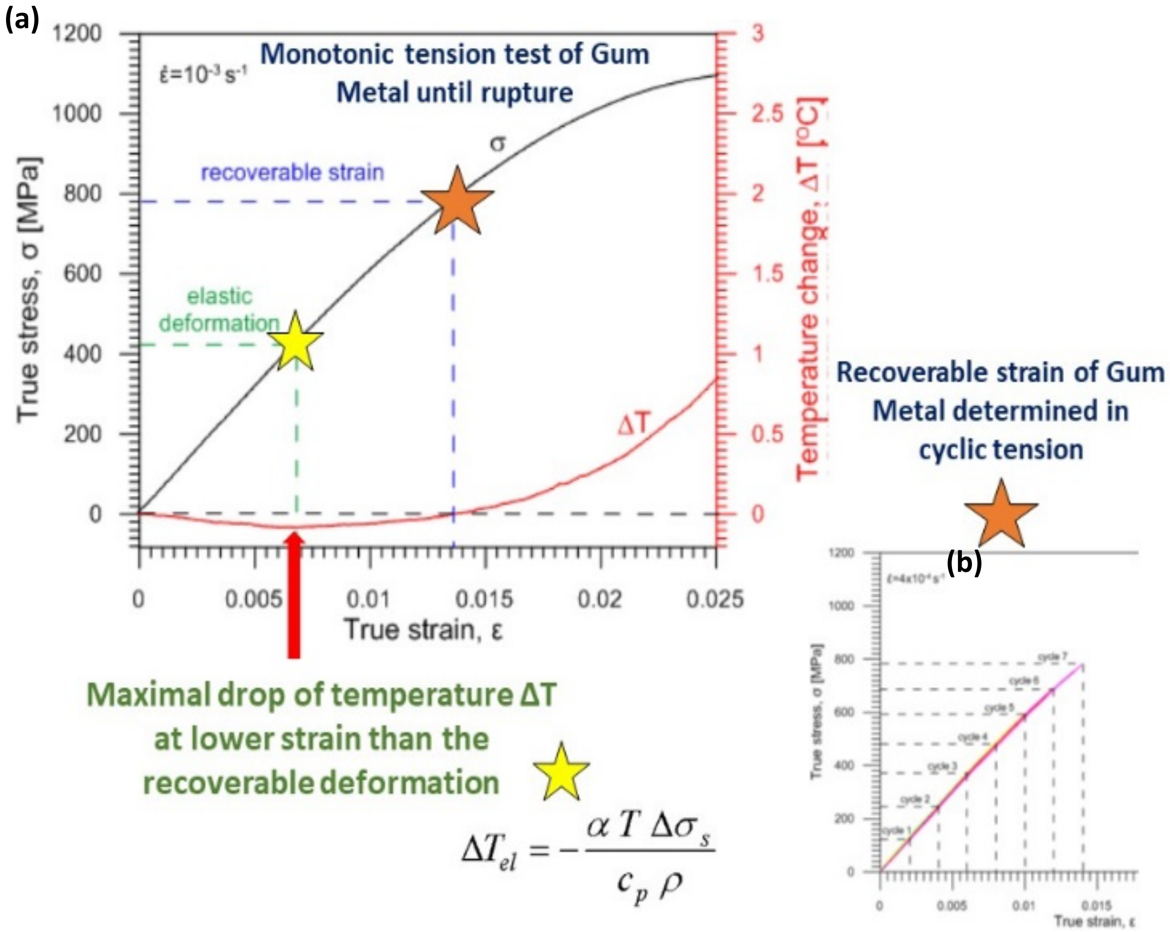

Fig. 2 (a) Stress σ and temperature change ΔT vs. strain ε curves of Gum Metal under tension indicating exothermic nature of recoverable deformation; (b) Determination of the recoverable strain range

Original experimental results included full-field deformation and infrared measurements during selected loading schemes of Gum Metal under tension and compression on a testing machine using techniques of digital image correlation (DIC) and infrared thermography (IRT) have been obtained. Among others, the nonlinear, mechanically recoverable deformation range of the Gum Metal was determined by performing cyclic tension with a small strain step. The analysis of the average thermal response of Gum Metal under tension revealed that the maximal drop of temperature ΔT occurs at lower strain than the recoverable deformation, as shown in Fig. 2 (a). It means that the activity of stress-induced unconventional deformation mechanisms was found to be exothermic during the loading. This finding is in line with the mechanism of stress-induced activity of martensite nanodomains observed at the University of Tsukuba which cause an apparent dissipative behaviour.

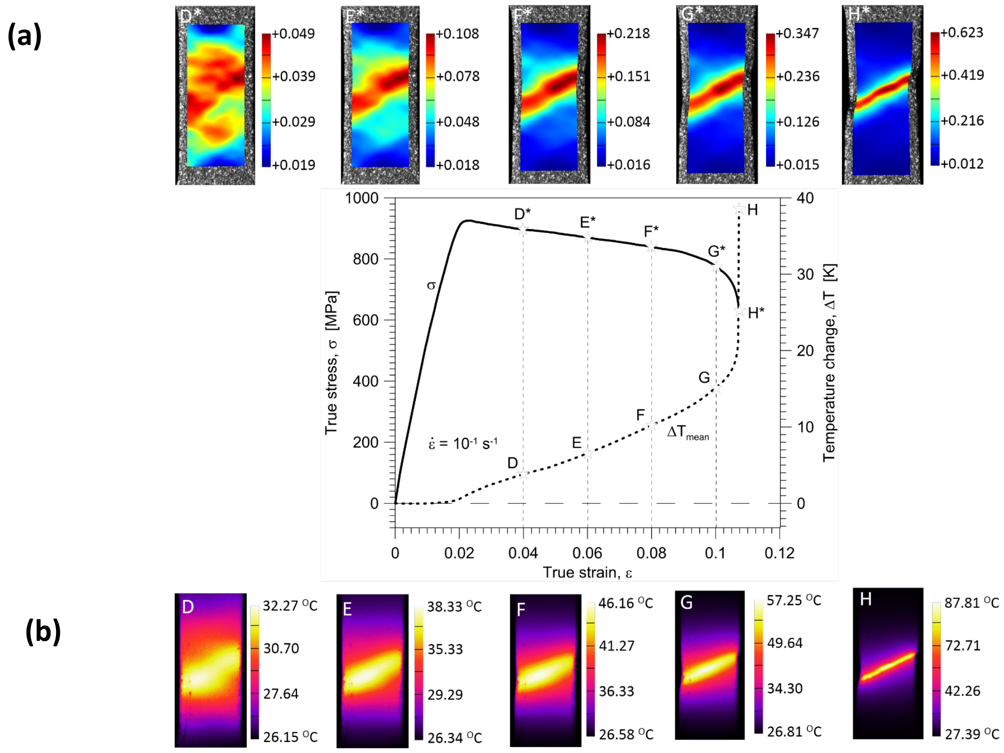

Fig. 3 Evolution of (a) deformation obtained by DIC and (b) temperature fields obtained by IR techniques captured at selected stages of the Gum Metal tensile loading (D, E, F, G) untill rupture (H).

Furthermore, it was demonstrated that Gum Metal is very sensitive to the strain rate which was manifested by mechanical and thermal responses of the alloy subjected to monotonic tension at selected strain rates. In particular, the analysis of the evolutions of deformation and temperature fields captured at selected stages of Gum Metal tension was important for understanding the strain rate sensitivity of the alloy exhibited particularly in the plastic regime of deformation (Fig. 3) [7, 11].

Investigation of thermomechanical properties of PU-SMP with partners from Japan was conducted on the samples provided by S. Hayashi in frames of the projects supported by the JSPS and National Science Centre [8, 9]. Recently additive manufacturing has been developed for a Shape Memory Epoxy (SMEp) [10].

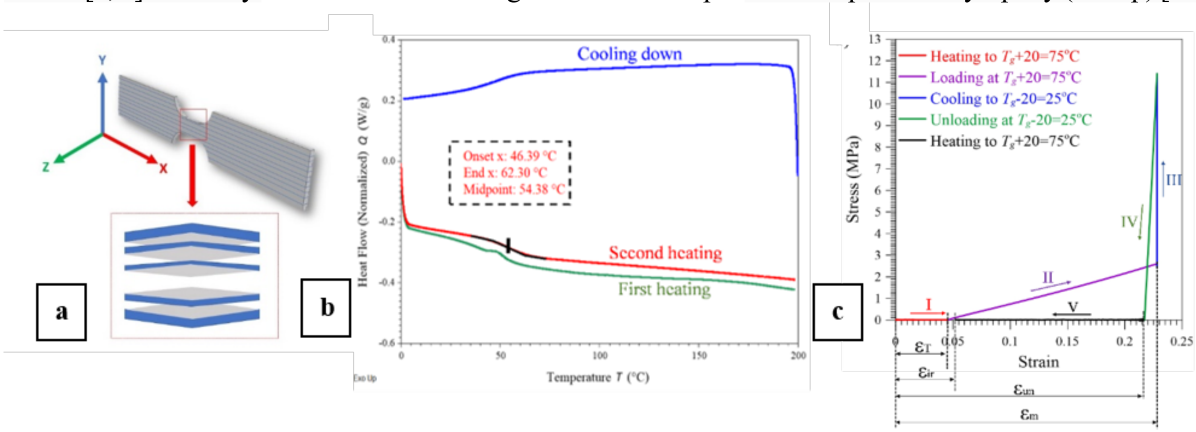

Fig. 4 (**a**) Schematic of SMEp specimen printed layer-by-layer from the lateral edge with SLA 3D printing; (**b**) DSC results (**c**) SMEp stress-strain curve obtained from thermomechanical loading cycle.

Concluding remarks

Long experience with infrared technique and possibility of using fast and sensitive infrared camera enable us to contribute to the research on Shape Memory Alloys, Shape Memory Polymers and Gum Metals

Coordinators of successfully developing international collaboration with Romania (Mariana Cristea) and Spain (Andre Dias Lantada) appreciate the obtained results and quality of innovative material, e.g. Polyurethane shape memory polymer PU-SMP, purchased due to the collaboration with Japanese researchers.

New techniques, i.e. additive manufacturing that have been developed in the meantime allow for the development of new kinds of more advanced shape memory polymers, e.g. shape memory epoxy, leading to new challenges and interesting results.

Due to the long cooperation with Prof. Hisaaki Tobushi et al. some joint projects were conducted, unique results were obtained and many joint papers were published in recognized Scientific Journals from the Journal Citation Report JCR list.

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Prof. Elżbieta A. Pieczyska, was a JSPS postdoctoral researcher in Japan (2004-2006). She completed habilitation thesis "Experimental analysis of thermomechanical characteristics of Ti-Ni shape memory alloy and shape memory polymer" in 2010. She has supervised three doctors and obtained full prof. title in 2021. She still collaborates with scientists from AICHI Institute of Technology, Hitachi University and University of Tsukuba - Host Institution for JSPS PostDoc of supervised Dr. K.M. Golasiński [11].