## IRON-CONTAINING SUPERELASTIC ALLOYS FOR SUPERSTABLE AND EARTHQUAKE-RESISTANT STRUTURAL DESIGN

**[1]KoledovV.V., [1]KamantsevA.P., [1]KalashnikovV.S., [2]KoshelevA.V., [1]DilmievaE.T., [3]LosA.S., [1]MashirovA.V., [1]KuchinD.S.,[6]LarchenkoV.V., [4]TaskaevS.V., [5]SampathV., [1]S.V. vonGratowski, [1]ShavrovV.G.**

*[1]Kotelnikov Institute of Radioengineering and Electronics of RAS, Moscow, Russia*
*[2]Lomonosov Moscow State University, Moscow, Russia*
*[3]International Laboratory of High Magnetic Fields and Low Temperatures, Wroclaw, Poland*
*[4]Chelyabinsk State University, Russia*
*[5]Department of Metallurgical and Materials Engineering, Indian Institute of Technology Madras, Chennai, India*
*[6]Don State Technical University, Rostov-on-Don, Russia*
*E-mail: victor_koledov@mail.ru, vsampath@iitm.ac.in*

Ferromagnetic iron-containing Heusler alloys exhibiting shape memory effect (SME), such as Ni-Mn-Ga-Fe demonstrate reversible deformations of up to several % due to thermoelastic martensitic transition induced by magnetic field [1]. The iron-based, high-strength Fe-Ni-Co-(Al-Ta-B) alloy with superplasticity and reversible deformations of more than 13% with a tensile strength above 1 GPa is discussed in [2]. The tensile strength of this alloy is almost twice that for the highest stress for superelastic deformation in Ni-Ti alloys. In addition, this iron-containing alloy also shows high damping and reversibility of magnetization during loading and unloading processes. More recently, other iron-containing alloys exhibiting superelasticity have attracted attention [3-7]. The investigations of a nanostructured FeMnSi shape memory alloy produced via severe plastic deformation is done in [8]. The family of Fe-Ni-Co-(Al-Ta-B) alloys demonstrates unique physical properties: a wide temperature hysteresis of superelasticity, a change in magnetization over a larger range, and electrical resistance due to load, accompanied by high pseudoplasticity. In view of these properties, these iron-containing superelastic alloys are expected to be used for a wide range of practical applications, such as damping and functional materials. Significant interest in these alloys is caused by the quest for inexpensive structural materials for the fabrication of structures that are resistant to earthquakes, such as nuclear power plants, high-rise buildings, bridges and industrial facilities.

This report presents the results of the development of new Fe-Ni-Co-(Al-Ta-B) alloys, experimental study of structures made of them, occurrence of martensitic phase transitions due to temperature, stress as well as magnetic field. Particular attention is to be paid to the study of magnetic and functional properties of the alloys under high magnetic fields, namely, magnetic-field-induced SME, magnetoplasticity, elastrocaloric and magnetocaloric effects. The engineering approach to the super-resistant structural design is briefly discussed. In addition, the mathematical problems arising from the treatment of statically indeterminate systems, in which undetermined state is due to superelasticity and intermediate state of martensite-austenite equilibrium of the material under the action of the strong external load, are outlined.

The principles of superelasticity are illustrated in Fig. 1 a, where “flag-like” stress-strain curves of the superelastic alloy, such as Fe-Ni-Co-(Al-Ta-B) and TiNi (curves 1, 2), are represented schematically, compared with standard strain-stress curve for steel (curve 3). The characteristic features of the superelastic alloys are high reversible deformation, high strain, compared with conventional steel and also hysteretic (“flag-like”) character of the curve, explaining their outstanding damping properties (Fig.1,b).

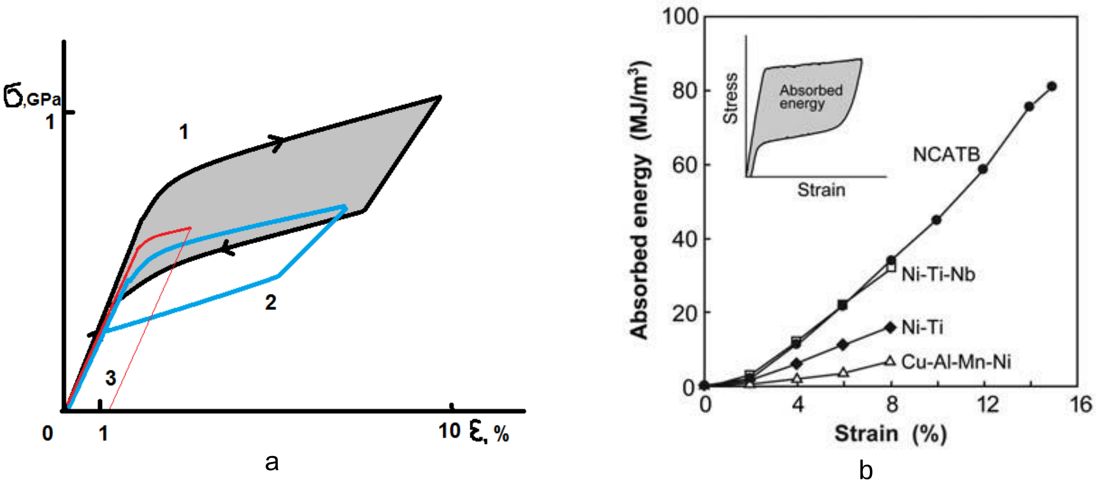


Figure 1 – (a) Stress-strain curves for superelastic Fe-Co-Ni-(Al-Ta-B) alloy – 1, shape memory TiNi alloy – 2, conventional steel – 3; (b) plot absorbed energy vs. strain for different shape memory alloys [2]

Figure 2 compares the bending strain of conventional steel (Fig.2,a) and superelastic Fe-based shape memory alloy (Fig.2,b), exhibiting completely reversible giant bending deformation under an external force, F. Both static overloads and dynamic deformations due to wind or earthquakes could be completely recovered without any technical assessment using this principle. Even larger magnitudes of deformation using the same amount of the superelastic alloy can be controlled utilizing the package design of superelastic beams (Fig.3). These kinds of large-scale structures are called «superstable» due to the fact that their completely reversible deformations are in principle several times larger than those of modern structures based on plastic inserts and shape memory wires. Figs. 4 and 5 demonstrate the concepts of the superstable completely reversible structures utilizing both damping capacity and high strength of superelastic beams and packages. The concrete structures also can be reinforced by superelastic beams giving rise to superstable walls and damping foundations.

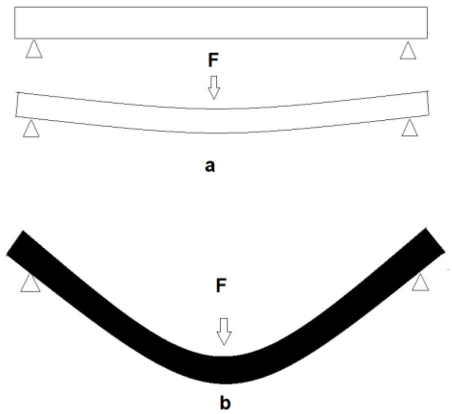


Figure 2 – The concept of giant reversible superelastic deformation: (a) normal elastic deformation of steel; (b) superelastic reversible deformation of the Fe-Ni-Co-(Ta-B) alloy for the design of superstable structures

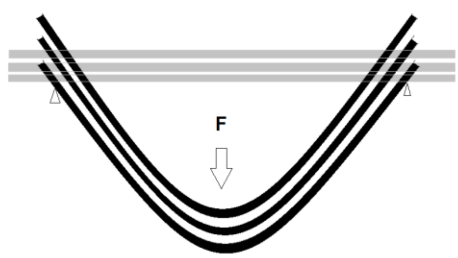


Figure 3 – The concept of package design of super elastic beams with giant reversible deformation for the superstable structures

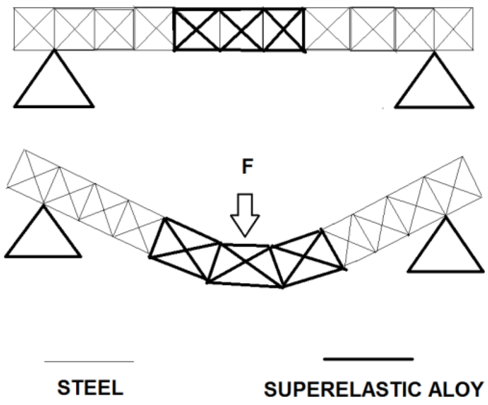


Figure 4 – The concept of superstable structure based on superelastic beams with giant completely reversible giant deformation

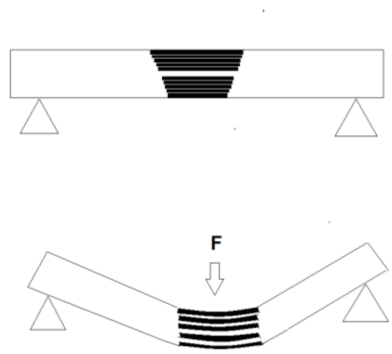


Figure 5 – Concept of the superstable structure based on the package of superelastic beams with completely reversible giant deformation

In designing the superstable structures a specific difficulty relating to the static indeterminacy of the problem arises. The traditional static indeterminacy arises from the presence of additional or «extra» connections. Due to «flag-like» stress-strain curves of the superelastic materials new mathematical methods should be applied in order to overcome the problem of description of behavior the composite materials with inserts of the alloy with martensitic transition, which under an external load go over to the intermediate state. Further work needs to be done in order to develop robust calculation methods for finding the most reliable and economical solutions.

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1. Cherechukin, A. A., et al. (2001) Shape memory effect due to magnetic field-induced thermoelastic martensitic transformation in polycrystalline Ni–Mn–Fe–Ga alloy. Phys. Lett. A, 291(2), 175.
2. Y. Tanaka et al. (2010) Ferrous polycrystalline shape-memory alloy showing huge superelasticity. Science 327, 1488.
3. Bhowmick, S., Mishra, S. K. (2016)FNCATB Superelastic damper for seismic vibration mitigation. J. Intel. Mat. Syst. Str., 27(15), 2062.
4. Omori, T., Ando, K., Okano, M., Xu, X., Tanaka, Y., Ohnuma, I., & Ishida, K. (2011). Superelastic effect in polycrystalline ferrous alloys. Science, 333(6038), 68-71.
5. Omori, T., Abe, S., Tanaka, Y., Lee, D. Y., Ishida, K., and Kainuma, R. (2013). Thermoelastic martensitic transformation and superelasticity in Fe–Ni–Co–Al–Nb–B polycrystalline alloy. Scripta Mater., 69(11), 812-815.
6. Lee, D., Omori, T., and Kainuma, R. (2014). Ductility enhancement and superelasticity in Fe–Ni–Co–Al–Ti–B polycrystalline alloy. J. Alloy. Compd., 617, 120-123.
7. Tanaka, Y., Kainuma, R., Omori, T., Ishida, K. (2015). Alloy Design for Fe-Ni-Co-Al-based Superelastic Alloys. Materials Today: Proceedings, 2, S485-S492.
8. Gurau, G., Gurau, C., Sampath, V., Bujoreanu, L. G. (2016). Investigations of a nanostructured FeMnSi shape memory alloy produced via severe plastic deformation. Int. J. Miner. Metall. Mater., 23(11), 1315-1322.