First Elucidation of Mechanism of Shape Memory Effect Driven by Magnetic Field

– New Development toward Practical Application of High Output Actuators –

[Abstract] A research group centering on Associate Professor Akio Kimura of Graduate School of Science, Hiroshima University,, and Mr. Mao Ye, a graduate student in the same university, Professor Masafumi Shirai and Assistant Professor Yoshio Miura of the Research Institute of Electrical Communication, Tohoku University, Dr. Keisuke Kobayashi, Beamline Station Leader and Dr. Shigenori Ueda, Researcher, of the National Institute for Materials Science (NIMS), Professor Ryosuke Kainuma of the Institute of Multidisciplinary Research for Advanced Materials, Tohoku University, and Professor Takeshi Kanomata of the Division of Engineering, Graduate School of Tohoku Gakuin University, elucidated the mechanism of structural phase transition shown in ferromagnetic shape memory alloys for the first time, using hard X-ray photoelectron spectroscopy (HX-PES) at the large synchrotron radiation facility SPring-8 and a computational technique, so-called, a first-principles calculation. Proposal for general principles of the design on next-generation actuator materials based on ferromagnetic shape memory alloys is expected to be possible as a result of these achievements.

[Background]

Ferromagnetic shape memory alloys, which are a new class of materials, show the shape memory effect, having the properties of ferromagnets. The materials, which convert a displacement or force to a mechanical energy by changing temperature, or by applying magnetic fields, electric fields, etc., are called actuators. Typical actuators include the piezoelectric materials, magnetostrictive materials, and shape memory alloys. Among these materials, the shape memory alloys show the large output generation with strain and force, and the generated energy density of shape memory alloys is approximately 1000 times higher than those of the piezoelectric and magnetostrictive materials. However a working speed in shape memory alloys is regulated by thermal conductivity, these materials have a weak point of slow speed of movement.

In 1996, a research group of Massachusetts Institute of Technology (MIT) discovered that Ni_2MnGa, which consists of nickel (Ni), manganese (Mn), and gallium (Ga), produces a large magnetic field induced strain of 0.15%. This discovery dramatically accelerated research on ferromagnetic shape memory alloys. Since the displacement of this ferromagnetic shape memory alloy can be controlled by a magnetic field, development of applications as a magnetic field induced actuator, which enables high-working-speed, is expected. Furthermore, the MIT research group also reported that the magnitude of strain in Ni_2MnGa was as large as approximately 10%. However the principle of this phenomenon occured by the movement at the twin crystal interface, the generated force reached only several megapascals (MPa). This drawback had been a major obstacle to practical applications.

Since new ferromagnetic shape memory alloys have been discovered in 2004,, considerable progress toward practical applications has been started, originating in that these alloys show a large strain output by applying a magnetic field. The materials in the new group are ferromagnetic shape memory alloys based on ternary alloy systems of Ni_2MnZ (Z=In, Sn, Sb), which consists of Ni and Mn, with indium (In), tin (Sn), or antimony (Sb) as the third element. Although Ni_2MnZ itself is a ferromagnetic material, this material does not show the shape memory effect such as the above-mentioned Ni_2MnGa. In the case of the $Ni_2Mn_{1+x}Z_{1-x}$ alloys with excess Mn, the alloys exhibit for the first time the large shape memory effect. Particularly it was reported in 2006 that in case of the Ni-Mn-In based alloy, the original structure was completely restored by an induced magnetic field and in principle a force as large as 100MPa was possible to be generated by a magnetic field. Therefore these materials are much attracting in these days.

At high temperature, the basic crystal structure of the alloy is in a cubic phase. In contrast, the structural phase transition from a cubic phase to a complex structure occurs when the material is cooled to a certain temperature. This phenomenon is called the martensitic phase transition, although understanding of the mechanism responsible for this structural phase transition from the microscopic viewpoint is considered to be extremely important for developing practical ferromagnetic shape memory alloys with high-functionality. But almost no research on this kind of study has been done in the world.

[Research techniques and results]

In order to elucidate the mechanism of the martensitic phase transition in $Ni_2Mn_{1+x}Z_{1-x}$ alloys, which is the new class of ferromagnetic shape memory alloys, from the microscopic viewpoint, we have measured the electronic structure of this alloy system by hard X-ray photoelctron spectroscopy at the NIMS contract beamline BL15XU located at the advanced large synchrotron radiation facility SPring-8, and have performed a first-principles calculation.

As a result of the analysis using the above methods, we found that the electronic states of Ni show the energy splitting, which strongly depends on the direction of spin, and the minority spin states of Ni strongly relate to the martensitic phase transition mechanism. Our group also found for the first time that the minority spin states are completely occupied by electrons and do not relate to the martensitic phase transition in Ni_2MnSn, which is the mother material. In contrast, the presence of excess Mn modifies the minority spin states of Ni and creates vacancies in the states along with the energy splitting, changing the crystal structure. Thus we found that the excess Mn in this alloy system plays an important role in the martensitic phase transition in the above-mentioned mechanism.

[Significance of research results]

1. The mechanism of the structural phase transition in a ferromagnetic shape memory alloy, which had not been clarified in previous research, was elucidated for the first time from the viewpoint of the electronic structure.

2. Based on these research results, proposal for general principles on the materials design of

next-generation actuators based on high-performance ferromagnetic shape memory alloys is expected.

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