Twin microstructure in Ni-Mn-Ga alloys

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Phase transformations are one of the important structural phenomena for creating and tailoring of microstructure of materials. For functional materials, phase transformations are of utmost importance since it is the basis for their functions and properties. Shape memory effect is one of the examples, which is based on a thermally or magnetically controlled reversible martensitic transformation. Due to their application potential, intelligent smart adaptive systems have arisen much interest. Magnetic shape memory alloys (MSMAs) like Ni-Mn-Ga belong to these materials due to a shape change in response to a significant structural orientation change in the magnetic field.

The effect observed in Ni-Mn-Ga alloys is the so-called magnetic field induced strain (MFIS), i.e. martensite twin variant rearrangement in an applied magnetic field resulting in a strain up to 12% [1, 2]. This effect makes the material attractive for a number of technological applications like actuators, sensors and harvesters. Low twinning stress increases the efficiency of MFIS.

Besides crystallographic slip, deformation twinning is the most prevalent mechanism of plastic deformation in many materials. In the classic definition the relationship between twin and parent lattice has to comply with an invariant plane and can be realized either by a reflection in some plane or by a rotation of 180° about some axis. In the 5M structure the twinning relationship can be satisfied by rotation of 86.4° about the [100] common a-axis. In five-layered modulated (5M) Ni-Mn-Ga martensite, MFIS can be realized by the motion of type I and/or type II twin boundaries [3-6]. The type I twin plane is determined to be (101) while the type II deviates about 6 degrees from the type I having irrational numbers. Type II twin boundaries have a very low twinning stress of about 0.05-0.3 MPa at room temperature while the type I twin boundaries about 0.8-1.2 MPa. Additionally, type II twin boundaries exhibit a very weak temperature dependence of the twinning stress over a broad temperature range 20-330 K, [7, 8]. This provides a strong application potential of 5M Ni-Mn-Ga alloys both at high and low temperatures.

Both type I and type II twin boundaries were studied previously using optical microscopy, X-ray diffraction (XRD) and theoretical considerations [5, 7, 8]. However, these methods could not reveal the fine features which may be crucial for explaining the twinning stress of type I and type II twin boundaries. A method which provides high spatial resolution and makes possible the direct combination of microstructural and crystallographic orientation information is EBSD technique. Using the modulated commensurate crystal structure model for 5M Ni-Mn-Ga martensite [3, 6, 9] the orientation analysis with all twin boundaries observed in 5M Ni-Mn-Ga is possible. Such a model takes into account the monoclinic distortion and long-periodic modulation which are neglected in tetragonal assumptions.

The initial microstructure of the Ni-Mn-Ga alloys is a typical self-accommodated microstructure of martensite. It is composed of macro, micro and nonotwins. In a typical martensitic transformation the high-temperature phase has a greater crystallographic symmetry than the low-temperature phase. Consequently, austenite may transform to several martensitic variants, the number of which depends on the change of symmetry during transformation. Generally, in a cubic-to-monoclinic transformation (5M case) twelve variants can be obtained. However, close examination of the high resolution EBSD mapping reveals that more than twelve orientations, as expected from the theory, exist in the 5M structure. Each of these variants may be split in some twin relations in different regions of the sample which differ from each other by about few degrees creating higher number of variants.

To achieve MFIS in Ni-Mn-Ga alloys, a procedure composed of successively compressing has to be applied. This procedure is called training process. As a result the twinning stress is reduced and the twinning strain is maximized. Training allows reducing the twinning stress and maximizing the twinning strain by removal of these variants which c-axes is unfavorable oriented with respect to the compression axis [10]. However, this training allows to obtain the single variant state only with respect to the so-called c-axis. After such a procedure other kind of twin boundaries (so-called modulation and a/b boundaries) still exist which can been shown by EBSD. The modulation boundaries or modulation itself were mostly neglected in the previous works on the 5M structure. Therefore, this structure was very long time assumed to be tetragonal. However, recent studies clearly showed that the 5M martensite possess a modulated monoclinic structure with a very small difference in the *a* and *b* lattice parameters [9, 11]. This difference and modulation are the reasons for the “new” boundaries. Using only the tetragonal assumption they cannot be detected. As the twinning stress is a crucial property of the material and the additional boundaries seem to inherently accompany mobile twin boundaries (responsible for MFIS), the exact role of them should be further studied. As already shown in [12] the {100) compound twin boundaries may increase the twinning stress and may also be responsible for the scatter of twinning stresses observed for 5M Ni-Mn-Ga martensite. Such compound twins are also observed adjacent to type I and/or type II twin boundaries. Thus, there exists a number of ways in which the modulation boundaries can be distributed.

Recently, using a special loading sequence and synchrotron radiation, it was found a mechanical treatment which allows to remove the modulation twinning [6, 13]. High energy of synchrotron radiation was used to achieve measurements in transmission geometry resulting in good statistics due to the representative sample volumes. Moreover, synchrotron radiation allows very easy detection of modulation revealing four extra satellite reflections. To obtain a single variant state with respect to the modulation direction, a plain strain deformation device was used which allows loading of the sample along the face diagonals. The sample was placed under 45° and -45° between the grips giving compression along the [110] directions. In such a way a variant with the shorter *a-b* plane diagonal (along modulation direction) was obtained. The next step which is still unknown, will be to control (remove) the a/b lamination. The a/b-lamination can be alternatively controlled by a thermal treatment in selected alloys, allowing to switch between states with a/b-lamination and completely without a/b-lamination.

Thus, the scatter of the twinning stresses observed for type I and type II twin boundaries indicates that the simple distinction between these two types is not sufficient to explain the twinning stress of this material. Based on the present results it is concluded that {100) compound twin boundaries strongly affect the twinning stress. It is also strongly suggested that both modulation and a/b boundaries increase the twinning stress and as a consequence decrease the efficiency of such a material. To further optimize this process the underlying interaction mechanisms between different kinds of twin boundaries have to be explored and understood on physical grounds.

Chmielus *et al.* [14] suggested that Ni−Mn−Ga samples with densely twinned microstructures are beneficial for actuator applications due to enhanced fatigue performance and relaxed geometrical constraints in an actuator in comparison to coarse twinned microstructures. The densely twinned microstructures also result in good repeatability and stability of MFIS [14] as well as faster MFIS in pulsed magnetic field-induced actuation. Thus, it can be expected that the densely laminated twin microstructure consisting of type II twins will exhibit highly efficient and almost temperature independent actuating performance and simultaneously repeatability, stability and long fatigue life due to densely twinned laminated microstructure. As a matter of fact the combination of fine twin structure and type II twins presented in [15, 16], will be most beneficial for actuator application [5]. Such a possibility has an important technological aspect, as type II twins exhibit a significantly lower and almost temperature independent twinning stress when compared to type I twins. Additionally, fine twinned microstructures result in good repeatability and stability of MFIS as well as faster MFIS in pulsed magnetic field-induced actuation.

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