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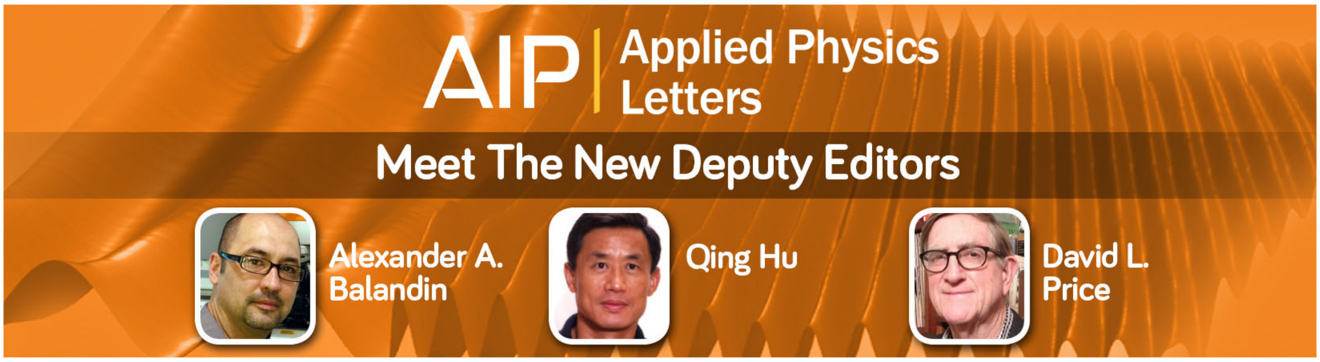

APPLIED PHYSICS LETTERS **106**, 041908 (2015)

# Jerky magnetic noises generated by cyclic deformation of martensite in $Ni_2MnGa$ single crystalline shape memory alloys

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It is shown that during periodic deformation of martensitic $Ni_2MnGa$ single crystalline alloy jerky magnetic noises are emitted. Above a threshold limit in the deformation amplitude, the noise energy per deformation cycle showed increasing tendency with increasing deformation. Energy and amplitude probability distributions of the noise were characterized by power law functions. The energy exponents were independent of the deformation amplitude in the investigated range. The decrease of the noise energy as well as power exponents with increasing magnetic field was interpreted by the decrease of the multiplicity of the martensite variants. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4907227]

In $Ni_2MnGa$ ferromagnetic shape memory alloys, giant deformations can be induced in martensite either by the application of external stress or magnetic field.[1] This superplastic deformation can be as high as 12% (see, e.g., Ref. 2) and can have many applications such as actuators and shape morphing.[1,3,4] Thus, understanding of the underlying mechanism of such deformation is very important for practical employments, since, e.g., the magnetically induced reorientation of the martensite twin variants can provide fast response with large deformations. The large strain is the consequence of the change of the martensite microstructure: the so called domain switching takes place by the motion of twin boundaries between two differently oriented martensite variants. Due to the fact that martensite variants usually contain internal twins, the martensite has adaptive character resulting in phase modulation[5] and, e.g., two variants of a tetragonal martensite phase can be connected with a regular arrangement of twin boundaries on the atomic scale.[6] This rich structural feature can be very important in determining the mobility of the twin boundaries. For example, recently, it was shown that in $Ni_2MnGa$ 10 M (modulated) martensite there could exist two types of twin boundaries (types I and II),[7,8] from which the type II has very high mobility. Accordingly, investigation of the kinetics of the above domain switching can be very useful in the understanding of twin boundary motion.

It is well-known that in austenite/martensite phase transformations, the phase boundaries have a stop and go type motion and thus the transformation has jerky character. Consequently, different noises (thermal, measured by DSC,[9] acoustic emission, AE,[10–12] magnetic noise[13]) can be detected. Thus, in $Ni_2MnGa$ alloys magnetic field induced Barkhausen-noise has been measured both in austenitic and martensitic phases.[14] Furthermore, at the martensite-austenite and intermartensitic transformations, magnetic noises can also be generated without application of external magnetic field,[13] or AE can also be detected during the austenite/martensite phase transformation.[10–12] The above noises can be characterized by power-like distribution functions[15]

$$P(x) \cong x^{-\alpha} \exp(-x/x_c), \tag{1}$$

($P(x)$ is the probability density, $\alpha$ is the critical exponent, and $x_c$ is the cutoff value), indicating a behaviour near to the self-organized criticality.

There is one publication,[16] in which acoustic emission activity was detected during stress induced martensite reorientation, while the austenite was acoustically inactive during loading and unloading. This was attributed to twinning process, indicating its jerky character, but no statistical analysis of the AE noise was carried out. Furthermore, in a recent lecture by Salje,[17] it was illustrated that statistical analysis of such AE noises should be possible and, using model considerations, the estimation of critical energy exponents was also presented.

It is expected that, due to magnetoelastic coupling, magnetic noises can also be detected during twinning process: the twin rearrangement can initiate jerky type magnetic domain wall motions too. Thus, in this paper, we present experimental results on statistical analysis of magnetic noises generated by cyclic deformation of martensite in $Ni_2MnGa$ single crystalline samples. The effect of constant external magnetic field on the noise characteristics was also investigated.

$Ni_{50}Mn_{28.5}Ga_{21.5}$ single crystalline samples ($1 \times 2.5 \times 20$ mm, purchased from Adaptamat Co. Finland) were subjected to periodic bending deformation in static magnetic field up to 0.725 T. The longitudinal faces of samples were parallel with the {100} austenite crystallographic planes. All measurements were carried out at room temperature, where the samples were in 5 M (10 M) modulated martensitic state. The periodic bending deformation, with 120 s time of period, was performed by an electromechanical system shown in Fig. 1. The sample was embedded into a silicon rubber block ($10 \times 25 \times 40$ mm) to ensure homogeneous deformation without strain localization at special parts of the sample with preferred variants. The direction of the external magnetic field was parallel to the longitudinal edge of the sample. The maximum strain at the surface of the sample was estimated to be 0.01. A detector coil with 300 turns was wounded on the sample. The induced magnetic noise was amplified and acquired by 200 ks/s sampling rate. The statistical data were evaluated off-line from the recorded signals.

 

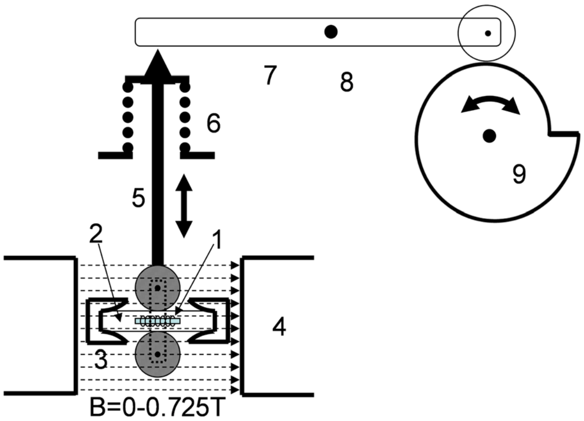


FIG. 1. Experimental setup, schematically. 1: sample with detector coil, 2: silicon rubber embedding material, 3: fixation, 4: magnet pole, 5: push-pull rod, 6: bias coil spring, 7: swinging arm, 8: pivot pin, 9: DC servo motor with eccentric driver.

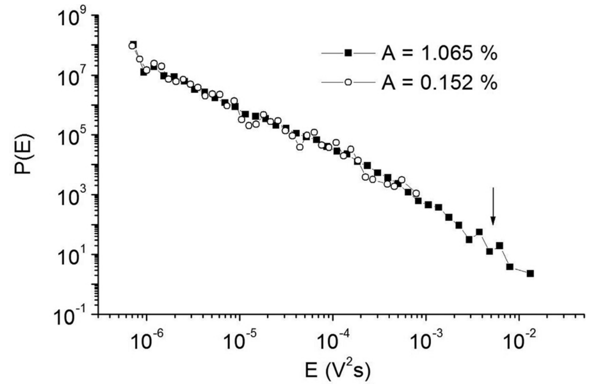


FIG. 3. Effect of the deformation amplitude on the energy distribution and on the energy exponent at B = 0.475 T. The arrow shows the cutoff value for A = 1.065%.

The evolution of the signal character with increasing deformation amplitude, A, at two different magnetic fields can be seen in Figs. 2(a) and 2(b). At high magnetic field (Fig. 2(a)), the signal shows a strongly asymmetric character, while at lower fields (Fig. 2(b)) the signals are more symmetric, and only a slight asymmetry appeared at larger deformation amplitudes.

The probability distribution of the amplitude, V, energy, E and duration time, t, can be described by power functions as given by Eq. (1). Fig. 3 illustrates that the energy distribution function extends over 4 decades of the peak energy and shows that the distributions and the energy exponent are independent of the deformation amplitude. The only plausible difference is that the distribution is extended to higher energy peaks for higher amplitudes. Similar power law behaviour was observed in the whole investigated deformation and magnetic field range. The critical exponents and cutoff values were estimated not only from the fitting of log P versus log E, log V, or log t, but the Maximum Likelihood method[18] was also used: the exponents were the same within the error limits.

Exponents of the energy ($\varepsilon$), amplitude ($\alpha$), and duration time ($\tau$) (evaluated from the distribution functions) are plotted on Fig. 4 as a function of the external magnetic field. All curves show about 20% drop in the low field range between B = 0 T and 0.1 T. Above this value, the $\varepsilon(B)$ function shows a saturation character, while for $\alpha$ and $\tau$ there is an increase at higher field values. The cutoff values for all the three distribution functions were independent of the external field at the same deformation amplitude and the average value for the P(E) functions is $E_{cutoff} = 5 \times 10^{-3} \pm 2 \times 10^{-3} V^2 s$ at A = 1.065%.

The total noise energy, $E_c$, calculated by the summation of the integrals of $V_i^2(t)$ for one cycle, versus A is shown in Fig. 5. Above a threshold limit, the slopes of the curves decrease with increasing external magnetic field.

The magnetic emission signals detected during the deformation process are clear evidences for the jerky motion of magnetic domain walls during domain switching. The decrease of the noise energy and the increase of the signal

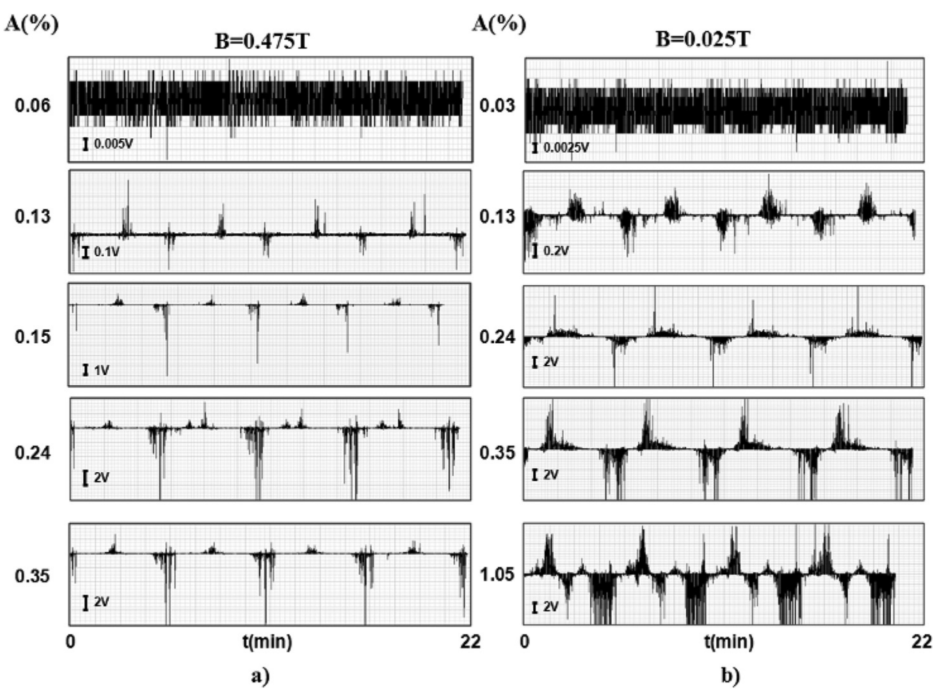


FIG. 2. Evolution of the signal character with increasing deformation amplitude, A, at higher (a) and lower (b) magnetic fields.

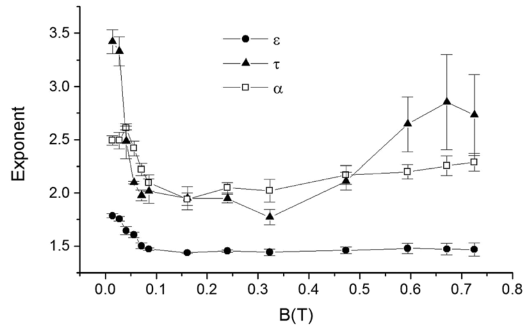


FIG. 4. Noise amplitude, energy, and duration time exponents as a function of magnetic field measured at A = 1.02%.

asymmetry with increasing magnetic field clearly indicate the competitive behaviour of the strain and magnetic fields.

The details of the above processes can be very important in understanding of high performance magnetic shape memory effect. It is well known that bending of such samples can create controlled twinned microstructures[19] and combined application of external stress and magnetic field can lead to a microstructure with fine twins containing highly mobile twin boundaries (with a very low twinning stress such as 0.1 MPa).[19–21]

In our case, the starting sample most probably had a random distribution of twin domains (thermally induced random twins). In the absence of external magnetic field, the periodic deformation can lead to a rearrangement into two differently ordered twin structures at positive and negative values of the maximal deformation amplitude, A, i.e., at compression and tension, respectively. Thus, the cyclic deformation applied at B = 0 T in fact seesaws the sample between two extreme twin configurations during which the rearrangement of the twin structure has jerky character and magnetic noise is detected. The application of the magnetic field direction gives different preferred orientation for the twins and tries to rearrange them towards a different single variant structure. According to Fig. 3 of Ref. 22, the switching magnetic and stress fields needed to start the twin reorientation in a multivariant twin state were about 0.05 T and 0.3 MPa, respectively. These values are in the range of stress and magnetic field applied in our experiments. Thus, in the non-deformed sample, gradually with the increasing magnitude of the external magnetic field, a more or less oriented twin structure develops and this is which is periodically deformed by bending. Of course, the twin structure at the maximal tensile as well as compressive deformations depends on the magnitude of the magnetic field: it is a result of the competition between the stress and magnetic fields.

The fact that the noise activity started at around 0.2% threshold shear strain indicates that below this no considerable twin rearrangements occurred. This threshold shear strain, within the scatter of our experimental data, is independent of the external magnetic field. In addition, this value is in a good agreement with the threshold compressive strain estimated from the curve corresponding to the two-variant structure (type I twin boundaries) in Fig. 9 of Ref. 7: 0.3%. The agreement confirms our interpretation described above.

The fall in the critical exponents for the energy, amplitude, and duration time between 0 T and 0.1 T (see Fig. 4) indicate that the relative number of large twin boundary jumps increases with increasing external magnetic field.

It is worth to mention that in Refs. 10 and 11, a similar field dependence of the critical exponents, obtained from AE measurements during austenite/martensite transformation, was observed. The drop in the energy exponent was about 25% and had a very similar character as the ε and E functions shown in our Figs. 4 and 6. The only difference is that the crossover (see Fig. 3 in Ref. 10 and Fig. 6 in Ref. 11) was at about 0.6 T, while in our Fig. 4 it is at about at 0.1 T. In Ref. 23, this behaviour was interpreted as follows: if the external magnetic field is at least in the order of the stress required to move the twin boundaries, twin plates can grow up to a relatively big size before meet each other, because the presence of the field decreases the multiplicity by selection of the growth directions of martensite plates. Thus, with increasing field fewer number of interactions dissipate higher energy, and the ratio of the numbers of low and high energy jerks decreases leading to the decrease of the critical exponent. A further increase of the field has no effect on the further selection of the preferred variants, and the exponents do not change. It seems that this qualitative explanation can be applied for our results as well. Note that there is an increase in values of α and τ with increasing B (Fig. 4). The interpretation of this calls for further considerations related to the details of the created noises.

Fig. 6 illustrates that although the relative number of large twin boundary jumps increases with increasing magnetic field, the dissipated energy decreases.

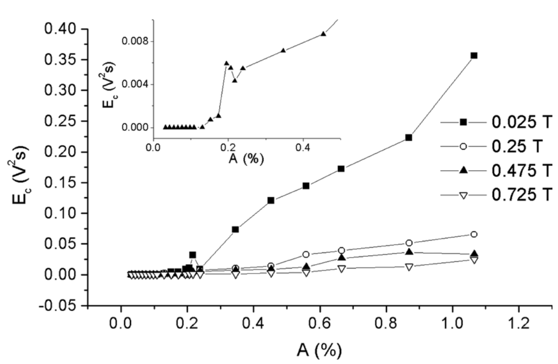


FIG. 5. Noise energy per deformation cycle as a function of the deformation amplitude, A. Inset shows the energy curve at B = 0.475 T in the vicinity of the threshold strain.

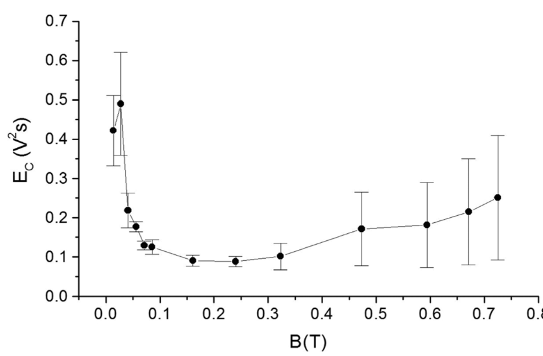


FIG. 6. Noise energy as a function of external magnetic field measured at A = 1.02% deformation amplitude.

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