Magneto-mechanical deformation of $\text{Ni}_{50}\text{Mn}_{28}\text{Ga}_{22}$ shape memory alloy

Sukup, Šimon^{1*}, Heczko, Oleg²

¹ Archbishop's Gymnasium, 76701 Kroměříž, Czech Republic

² Department of Magnetic Measurements and Materials, Institute of Physics CAS, 18121 Prague 8, Czech Republic

About the author

Šimon is primarily interested in applied physics and electronic engineering. He placed second in the Physics branch in the national round of Students' Professional Activities (SPA) in the Czech Republic, with his thesis on Ni-Mn-Ga shape memory alloy and a construction of a micropump. Šimon is a former student of the Archbishop's Gymnasium in Kroměříž and was also rewarded for his thesis by an award by the Learned Society of the Czech Republic in 2020. During his studies he took part in several summer schools and internships in the field of microelectronics and photonics. He is currently studying Electrical Engineering Bachelor at the Eindhoven University of Technology in Netherlands with the generous support from the Kellner Family Foundation and Bakala Foundation. This paper is an extract from his SPA 2020 thesis on research conducted at the Institute of Physics of the Czech Academy of Sciences.

Explanation for general audience

This work focuses on the pseudoplastic deformation of $\text{Ni}_{50}\text{Mn}_{28}\text{Ga}_{22}$ magnetic shape memory alloy. This phenomenon occurs due to the crystal reorientation, which can be induced mechanically or by magnetic field. This so-called giant pseudoplastic deformation that reaches 12 % can be observed even at the room temperature. In combination with martensitic transformation near room temperature, this phenomenon enables so-called magnetic shape memory effect. The recent research proposed utilisation of this alloy in solutions for aerospace engineering, electronic engineering and medical industry that have, however, not yet been widely implemented. It is, therefore, an effort of the current research to further explain the magneto-mechanical properties and to adapt the alloy parameters for a given application. In the first part of the study, the surface structures of samples were investigated using optical and atomic force microscopy. The measurements of mechanical deformation were conducted parallel to the optical measurements to study the effect of stress on the surface structures. Foremost, this work presented measurements and comparison of the energy needed for the elongation of the monocrystalline samples of the alloy in a magnetic field and under mechanical stress. To obtain relevant statistics, four different monocrystals were used and the measurement was repeated many times. In agreement with previous studies, the difference in the two modes of loading was observed in terms of energy. Additionally, the field needed to initiate the process of the elongation of samples was measured. Neither these results nor the consideration of the demagnetization field explained the observed discrepancies between the existing phenomenological model and the conducted measurements.

Magneto-mechanical deformation of $\text{Ni}_{50}\text{Mn}_{28}\text{Ga}_{22}$ shape memory alloy

Sukup, Šimon^{1*}, Heczko, Oleg²

¹ Archbishop's Gymnasium, 76701 Kroměříž, Czech Republic

² Department of Magnetic Measurements and Materials, Institute of Physics CAS, 18121 Prague 8, Czech Republic

* Corresponding author: simon.sukup@seznam.cz

This study deals with pseudoplastic deformation of $\text{Ni}_{50}\text{Mn}_{28}\text{Ga}_{22}$ alloy exhibiting mechanically and magnetically induced crystal reorientation. The new approach was introduced, taking into account crystals with single initial variant as well as nucleation of different orientation. Initially, observations from optical microscope and AFM (atomic force microscope) were correlated with the mechanical measurements from stress-strain machine to characterize boundaries between crystal variants. These observations were subsequently used to clarify the results of the mechanical deformation tests. By magnetizing samples in VSM (vibrating-sample magnetometer), analogous magnetic measurements to mechanical tests were conducted. The two types of measurements were then compared with respect to energy. The discrepancy found between the model and measurements is in agreement with previous studies. Some experimental factors and possible errors that may affect measurement have been discussed. Nevertheless, the observed differences remain an unresolved issue suggesting a need for a modification of the model.

Key words: Magnetic shape memory effect, magnetically induced crystal reorientation, mobility of twin boundary, ferromagnetic martensite.

(Submitted: 15 June 2021, Accepted: 26 November 2021, Published: 27 December 2021)

1 Introduction

In the field of intermetallics, Ni_2MnGa alloy and its doped variants with magnetic shape memory have received great attention in the last two decades after being first described in 1999. With its enormous pseudoplastic extension in the martensitic phase exceeding 10 % even at room temperature [1, 2], the Ni-Mn-Ga alloy proved to be a potential magnetically active alternative for a conventional Ni-Ti alloy. The Ni-Mn-Ga material is unique mainly due to the extremely low stress required for the formation and growth of crystal variants with a preferential orientation that is up to three orders lower than in Ni-Ti [3]. Furthermore, Ni-Mn-Ga is capable of faster actuation by magnetic field during the phase transformation compared to conventional alloys possessing shape memory induced by heat transfer. In recent years, these alloys have found potential applications in micro-electro mechanical systems, MEMs, either as an active element in circuits or sensors, mainly due to the ease of fabrication of their smaller-sized crystals [4]. Interesting and promising applications have also emerged in microfluidics as an active element in micropumps [5,

6]. This is not to mention the extensive applications of the alloy as a magneto-caloric material [7] thanks to the martensitic transformation. The aim of this work was to investigate the differences in the stress of boundary motion in terms of the energy required for reorientation in a magnetic field and under mechanical loading. The types of twinning boundaries and their influence on the resulting actuation behavior were also characterized during the measurements. The results of the measurements and further research can thus contribute to a successful use of single crystals for actuation.

2 Shape memory and crystal reorientation

In Ni_2MnGa we encounter two basic crystalline structures. The highly symmetrical cubic phase common to most Heusler alloys is the cubic face-centred L21 crystal lattice called austenite. In the case of our alloy, the lattice parameter is $a_A = 0.582 \text{ nm}$ [8]. However, when the temperature is lowered, namely for $\text{Ni}_{50}\text{Mn}_{28}\text{Ga}_{22}$

Figure 1: Heusler $L2_1$ unit cell (austenite) with the space group.

Figure 2: Basic cell of martensite.

to approximately 320 K, this high temperature phase is transformed into a new low-symmetrical structure called martensite (figure 2) [8]. If modulation of the crystal lattice is disregarded, the martensite unit cell of Ni_2MnGa can be approximated to tetragonal. The modulation causes slight monoclinic and orthorhombic distortion and is responsible for some of the types of martensite transitions [9].

In the case of crystal reorientation, a transition occurs in the martensitic phase between crystal structure variants that differ only in their basic cell orientation. These variants, also called twins, are separated by a twin boundary, which is highly mobile [2]. Its schematic representation is shown in figure 4.

During the crystal reorientation, entire layers of atoms are cooperatively displaced without structural disruption of the crystal. Moreover, the displacements of atoms in the vicinity of the twin boundaries are small compared to the interatomic distances, only tenths of an ångström [10].

Figure 3: An illustration of the crystal reorientation induced by force or magnetic field on the right. The space group is $P2_1/m$ in the case of 10M modulated martensite. In the figure it is approximated to $I4/mmm$. Lattice constants a_M , b_M , c_M and crystallographic directions are related to the parent phase of austenite lattice.

Figure 4: Diagram of a twin boundary is on the left. Surface tilt that makes the optical observation possible is ϕ . A resultant twinning laminate on the surface of monocrystal observed with the use of C-DIC (differential interference contrast) is on the right.

3 Structure of twinned martensite and twin boundary movement

When a monocrystal is subjected to an external field or mechanical stress, the crystal reorientation and the boundary movement take place. The boundary movement under mechanical loading occurs due to the shorter dimension c_M of the lattice compared to a_M , b_M in the [100] and [010]. In addition, Ni_2MnGa exhibits strong uniaxial anisotropy in the c_M direction with a hard axis of magnetization perpendicular to it. This strong coupling between martensitic and ferromagnetic microstructures enables so-called magnetically induced crystal reorientation (MIR).

The reason for the motion of the individual twinning boundaries during MIR is the difference in the energies of the two crystal orientations [11] in the magnetic field. The high difference of energies achieved in relatively low fields of around 0.65 T is only possible due to the ferromagnetic nature of the alloy and hence results in high susceptibility values and high magnetic anisotropy, with the K_u constant over $1.6 \times 10^5 \text{ J} \cdot \text{m}^{-3}$ [8]. A model of boundary motion in the field was first described by Ullako et al. [12, 13] and the reorientation mechanism, according

Figure 5: Twinning of type I and II. Plane of twin boundary is perpendicular to the figure. Two planes are depicted as one line as there is only slight mismatch between type I and II planes.

to the model, is identical when induced by the field and mechanically. In short, the model can be written as follows:

$$\Delta E_{\text{mag},V} \geq \sigma_{tw} \epsilon_{\text{max}}, \quad (1)$$

where σ_{tw} is the stress required for twinning, and in the tetragonal approximation with $a \cong b$, $\epsilon_{\text{max}} = 1 - c/a$, and is thus the theoretical maximum of the sample strain. $\Delta E_{\text{mag},V}$ is the sum of the difference in Zeeman energy together with the difference in anisotropic energy between hard and easy magnetization crystal variant in the external field per unit volume.

Since the derivative of the potential energy is negatively related to force, the field acts as an alternative source of stress σ_{mag} similar to mechanical measurements. From the model of Ullako et al. [12, 13] it follows that:

$$\sigma_{\text{mag}} = \frac{|\Delta E_{\text{mag},V}|}{\epsilon_{\text{max}}} \quad (2)$$

In room-temperature crystal reorientation with stoichiometry close to Ni_2MnGa , we encounter a 10M modulated martensite in which there are 12 possible orientations of the crystal structure [14]. These give rise to 5 types of twinning differing in symmetry, however, only the movement of the type I and type II twin boundaries, where the orientation of the c_M changes, is involved in the geometrical changes of the sample.

4 Experimental details

Five single crystalline samples of nominal composition $\text{Ni}_{50}\text{Mn}_{28}\text{Ga}_{22}$ and different origin were used for the measurements. All samples were cut from the ingot along the crystallographic planes of the austenite parent phase to secure the right orientation of c_M . The samples were then mechanically grinded and electropolished. Due to the composition of the samples, only 10M martensitic structure was present during the measurements at the room temperature. As $a_M \cong b_M > c_M$, only the orientation of c_M lattice constant during the type I and II boundary movement caused the deformation in both types of measurements.

Two modes of loading inducing crystal reorientation were conducted on the five samples using the custom-

Figure 6: Magnetization curves of a single variant with c -axis (easy axis of magnetization) along and perpendicular to the magnetic field on the left. At magnetic field marked H_{sw} , the MIR occurred, resulting in a large jump in magnetization. The difference of magnetic energy is marked by blue filling.

made stress-strain device and vibrating sample magnetometer (VSM). Prior to each of the measurements, samples contained only one variant with the c_M axis in the direction perpendicular to the applied force or magnetic field.

During the mechanical experiments the samples were pressed by the steel sheet onto stress sensor Honeywell FSG010WNPB with repeatability error 0.2 %, pressure error 0.5 % and resolution 0.0098 N. The displacement was measured by the embedded sensor with precision reaching a few microns. This device allowed measuring the stress only during loading and not during the pseudo-plastic elongation of the specimen. The whole measurement was recorded using a Raspberry Pi.

The stress-strain device was positioned under the optical microscope Axio Imager 2 of the company Zeiss to compare the measurements with observations of surface twinned structure in real time. The modes used for the observation of surface relief were the circular differential interference contrast (C-DIC) and the polarizing contrast.

During the magnetic measurements, the samples were magnetized using VSM, which uses electromagnetic induction caused by the vibrating sample to sense its stray field. Before each measurement, the sample was placed into the cavity so that the sample was magnetized in the direction of its hard axis of magnetization before the MIR was initiated. The homogeneous field in the cavity was induced by two electromagnets with the range of ± 2 T. Thanks to the homogeneity of the field, no mechanical pressure was exerted on the sample.

The energy per unit volume needed for the reorientation during both modes of loading was calculated from the graphs by numerical integration using trapezoidal rule as indicated in Figure 6. Energy of stress strain curves was calculated to the point of pseudoplastic limit so that the elastic deformation did not influence the measurement.

Figure 7: On the right, stress-strain curve with a red filling indicating energy needed for reorientation. The progress of twin variants redistribution is schematically shown above the plot.

Only the measurements where the whole sample reoriented and no nucleated variant was present beforehand were considered.

The work done by magnetic field is calculated as the closed loop area of the magnetization curve in the first quadrant. The example of measurements is depicted in Figure 6.

This work done by the magnetic field is necessary for nucleation or formation of a new crystal variant with easy axis of magnetization in the field direction and growth of these variants by moving the twin boundaries. Thus, it consists of two components which, however, cannot be distinguished in this arrangement (quasistatic measurement). Therefore, we report a single energy value for both mechanically and magnetically induced reorientation.

To calculate the energies during magnetization, a demagnetization field correction was necessary. The demagnetization factors of the samples were calculated according to the relation (2) in reference [15]. The hysteresis, which is minor compared to the effect of MIR, was also neglected in the measurements. Since the measured magnetization in [emu] units is an absolute value that depends on many parameters such as a position and size of the sample, in order to determine the energy, it was first necessary to scale the magnetization axis so that the highest magnetization value corresponds to the known value of the Ni-Mn-Ga saturation, which is 0.65 T [2].

5 Results

5.1 Mechanical measurements

Magnetic and mechanical measurements were performed repeatedly until structural changes were recorded by the optical microscope and stress-strain device or until the sample was fractured. The samples were tested for relaxation during the measurements, but the stress did not decrease by more than 3 % for any sample

Table 1: Energy per unit volume [J/m^3] used for crystal reorientation of samples during mechanical compression.

	B1	ETO	ETO-L	ETO-S	SC
Average	37 518	62 156	72 068	52 363	46 933
Dev.	3405	4485	6669	4256	4359
Dev. [%]	9	7	9	8	9

Figure 8: Comparison of samples in terms of stress-strain curves. ETO-L and ETO-S were obtained from broken sample ETO. They did not sustain damage except the area of the fracture. Despite their origin, the nature of the sample measurements varied significantly throughout the extension interval.

even after several minutes. The resulting energy per unit volume for samples SC, ETO, ETO-L, ETO -S and B1 are recorded in following Table 2.

The corresponding stress-strain data for all samples are shown in Figure 8. Each plot was created by firstly interpolating each measurement of the individual sample to 1000 points and then making an average over all measurements for the sample. The measurements were interpolated to the maximum pseudoplastic deformation of the given sample.

Because total energy during compression is an indication of the quality of a given single crystal, which is highly susceptible to small disturbances during fabrication, significant differences between samples have been observed. Each sample appeared to be specific in its twin boundary formation and its propensity to nucleate a particular type of twinning in certain parts of its volume. Optical microscopy showed that a combination of Type I and Type II twinning boundaries were frequently present. The ratio of two components of such composed boundaries and the pressure required for their movement varies as they move and the resulting pressure is given by the combination of the pressures of the two variants. The results of the measurements in Figure 8 could be compared with those of pure type I and II. Selected plots of both types can be seen in Figure 9. In the case of type II, a pressure close to 0.1 MPa was measured. For type I, the pressure was close to 1 MPa on average. These observations agree with previous publications [2].

Figure 9: Mechanical measurements of type I and II boundary movement conducted on sample SC.

Figure 10: Boundary of the type I and II on the sample SC and the corresponding orientation of the planes of twinning, with the use of C-DIC.

The difference in the orientation of the two types of twin boundary can be seen in Figure 10, which was taken by an optical microscope.

5.2 Magnetic measurements

Magnetization measurements were performed on the aforementioned VSM. The ETO sample was broken which reduced the number of correctly measured values compared to the other samples. The last measurements immediately before the fracture, which may have been affected by the propagation of structural defects, were not taken into account. The measurements are shown in Table 4.

Unlike mechanical measurements, where strain was controlled, the independent variable is now an external field, which is analogous to pressure. Because of this fact, when moving the boundary, we do not determine the lowest field value necessary for reorientation, but the value that is necessary to produce a variant with orientation in the field direction. Since the field cannot be immediately

reduced, it cannot be determined whether a smaller field is sufficient for the boundary to move after nucleation. The actual energy required for field reorientation may then be lower. To investigate this, the value of the field required to move the pre-existing, pre-formed boundary (denoted H_{tw}) was measured.

The variants were nucleated so that their volume fraction did not exceed 5 % of the sample and they were nucleated randomly throughout the volume to simulate the situation of measuring crystals with single variant in the initial state before measurement (hereinafter with single variant) as closely as possible. The negligible mechanical energy used for nucleation is not taken into account. A relative error of the magnetometer measurement was neglected considering the much higher differences between individual measurements.

From the measured data, H_{sw} of the single-variant samples in Table 3 and the H_{tw} of the samples after nucleation Table 4 were measured. The ETO sample was not considered due to a lack of measurements. The error in the tables expresses the deviation caused by the set magnitude of the magnetometer voltage step.

Although H_{tw} is associated with energy, the calculation of the energy per unit volume is used for comparison with the mechanical measurements. The energy for reorientation in the presence of a twin boundary, i. e., with nucleated variant, are given in Table 5.

For all samples, the magnetization energy of the sample with already nucleated boundary was in always lower than that of the samples with one initial variant. With the exception of one measurement of the ETO-L sample (see Figure 11), the H_{tw} was considerably lower than than the H_{sw} . In the case of the ETO-L sample, the twins most likely remained present even after repeated mechanical straining that was supposed to create a single variant. The average H_{tw} was lower for all samples. The structural defects resulting from fracture may have acted as nucleation sites reducing H_{sw} . This was also reflected in the energy per unit volume measurements in Table 5.

6 Discussion

Despite the differences in the energies for the MIR of the individual samples (see Figure 8), a clear trend emerged that the average magnetization energy of all samples is higher than the average energy of the mechanical measurements. Since the measurements have shown that $H_{tw} < H_{sw}$, with the exception of the ETO - L sample, it is to be expected that when determining the energy from the magnetization curves of one variant, there is a significant decrease in the stress required to move the boundary compared to the stress required for nucleation. This is one of the reasons for the higher energy compared to mechanical reorientation. The second reason is the need to overcome the demagnetization barrier, where the emerging variant has larger demagnetization energy than the whole sample.

Table 2: Energy per unit volume [J/m^3] for MIR of crystals with one variant. Dev. denotes resulting mean deviation.

	B1	ETO	ETO-L	ETO-S	SC
Average	74137	88265	107120	84801	102690
Dev.	5967	13244	17863	14502	12696
Dev. [%]	8	15	17	17	12

Table 3: Switching field H_{sw} of samples after nucleation. Error is in absolute value.

	B1		ETO-L		ETO-S		SC	
	$H_{sw}\mu_0$ [T]	Error	$H_{sw}\mu_0$ [T]	Error	$H_{sw}\mu_0$ [T]	Error	$H_{sw}\mu_0$ [T]	Error
Average	0.18	± 0.01	0.20	± 0.01	0.20	± 0.01	0.27	± 0.02
Dev.	0.02	-	0.05	-	0.05	-	0.05	-
Dev. [%]	9	-	25	-	23	-	17	-

Table 4: Twinning field H_{tw} of samples with a nucleated variant. Error is in absolute value.

	B1		ETO-L		ETO-S		SC	
	$H_{tw}\mu_0$ [T]	Error	$H_{tw}\mu_0$ [T]	Error	$H_{tw}\mu_0$ [T]	Error	$H_{tw}\mu_0$ [T]	Error
Average	0.095	± 0.01	0.150	± 0.004	0.10	± 0.01	0.100	± 0.004
Dev.	0.007	-	0.001	-	0.005	-	0.002	-
Dev. [%]	8	-	0.74	-	5	-	0.06	-

Table 5: Energy per unit volume [J/m^3] needed for MIR after nucleation.

	B1	ETO-L	ETO-S	SC
Average	45 449	65 974	45 009	61 028
Dev.	3889	5959	2385	6738
Dev. [%]	9	9	5	11

Figure 11: Comparison of mechanical and magnetic measurements by box diagrams. Significant deviations from the normal distribution are probably due to stress redistribution. **Figure 12:** Comparison of H_{sw} of crystal with a single variant with H_{tw} of crystal with a nucleated variant by box diagrams.

Indeed, as previous study has shown [16], consideration of the magnetostatic energy of the variants and their magnetic interaction with each other results in an increase in H_{tw} when the dimensions of the nucleated variant are initially small and the demagnetization factor is high. The model in the publication fits the measurements in the case of the type II twinning boundary closely, but its validity for type I and combined boundaries has not been shown practically. This approach cannot fully explain such a high difference in energies of MIR compared to mechanical measurements.

The lower energy required for mechanical reorientation can also be partly explained by the redistribution of the stress state during deformation. While in the magnetic field the same field is applied to each part of the boundary and is thus homogeneous, this is not the case for the mechanical force. If relaxation occurs on part of the boundary, the mechanical stress is redistributed and increased in the unrelaxed part. This then causes the local barrier to be more easily overcome. However, the experiment conducted in this study measuring the total energy cannot be affected by this mechanism.

Although the effects discussed can explain most of the differences, the results obtained suggest that the overall mechanism of reorientation caused by the mechanical stress and the magnetic field is different. This is consistent with previous measurements. The results of the stress motion measurements of already nucleated boundaries [17] in 2015 showed a similar difference in the mechanical and magnetic measurements for most samples in terms of twinning stress.

Moreover, the maximum stress for reorientation is determined by the magnitude of the anisotropic constant K_u . Thus, magnetization does not achieve as high stress for boundary motion as mechanical loading, which partially reduces the energy per unit volume in MIR compared to mechanical measurements. In the absence of this effect, the actual energy per unit volume for MIR would be even higher.

Thus, we can only speculate that the actual energy required for MIR is higher than that of mechanical meas-

urements. However, to prove this claim we would have to be able to actually measure the lowest field required to move the boundary, which is infeasible given the speed of the MIR process and the high inductance of the VSM electromagnets.

These measurements involving the total energy open a new direction for investigating the detailed nature of the MIR and magnetic forces, that could be conducted by X-ray tomography or acoustic emission.

7 Conclusion

This work has primarily shown that the average volumetric energy or work required for MIR is higher than the mechanical work done during reorientation or pseudo-plastic deformation. This difference cannot be attributed to the demagnetization field alone. The results of this work thus contribute to the idea that the original model [12, 13] of MIR needs to be extended with more accurate theoretical calculations in the absence of approximations. Moreover, no study has yet accounted for the effect of the interaction of magnetic domains at the transition between variants, which may also account for the discrepancies measured. Further large-scale measurements would be needed to reach clear conclusions.

ACKNOWLEDGMENT

The work was done as part of activity "Otevřená věda" by Czech Academy of Sciences. Author thanks for support CSF No. 19-09882S. Author would also like to thank Dr. Oleg Heczko for professional guidance and support during the research.

ABBREVIATIONS

VSM	vibrating sample magnetometer
MIR	magnetically induced crystal reorientation
H_{sw}	switching field, needed for nucleation of twin boundary
H_{tw}	twinning field, needed for movement of existing boundary

References

- (1) Sozinov, A.; Lanska, N.; Soroka, A.; Zou, W. *Applied Physics Letters* **2013**, *102*, 021902, ISSN: 0003-6951, 1077-3118, DOI: 10.1063/1.4775677, <http://aip.scitation.org/doi/10.1063/1.4775677> (accessed 05/11/2021).
- (2) Heczko, O.; Scheerbaum, N.; Gutfleisch, O. In *Nanoscale Magnetic Materials and Applications*, Liu, J. P. et al., Eds.; Springer: Boston, 2009, pp 399–439, ISBN: 978-0-387-85598-1.
- (3) Wang, J.; Sehitoglu, H. *Acta Materialia* **2013**, *61*, 6790–6801, ISSN: 13596454, DOI: 10.1016/j.actamat.2013.07.053, <https://linkinghub.elsevier.com/retrieve/pii/S1359645413005739> (accessed 10/11/2021).
- (4) Stephan, J. M.; Pagounis, E.; Laufenberg, M.; Paul, O.; Ruther, P. *IEEE Sensors Journal* **2011**, *11*, 2683–2689, ISSN: 1530-437X, 1558-1748, DOI: 10.1109/JSEN.2011.2157489, <http://ieeexplore.ieee.org/document/5772903/> (accessed 10/11/2021).
- (5) Ullakko, K.; Wendell, L.; Smith, A.; Müllner, P.; Hampikian, G. *Smart Materials and Structures* **2012**, *21*, 115020, ISSN: 0964-1726, 1361-665X, DOI: 10.1088/0964-1726/21/11/115020, <https://iopscience.iop.org/article/10.1088/0964-1726/21/11/115020> (accessed 10/11/2021).
- (6) Smith, A. R.; Saren, A.; Järvinen, J.; Ullakko, K. *Microfluidics and Nanofluidics* **2015**, *18*, 1255–1263, ISSN: 1613-4982, 1613-4990, DOI: 10.1007/s10404-014-1524-6, <http://link.springer.com/10.1007/s10404-014-1524-6> (accessed 10/11/2021).
- (7) Planes, A.; Mañosa, L.; Moya, X.; Krenke, T.; Acet, M.; Wassermann, E. *Journal of Magnetism and Magnetic Materials* **2007**, *310*, 2767–2769, ISSN: 03048853, DOI: 10.1016/j.jmmm.2006.10.1041, <https://linkinghub.elsevier.com/retrieve/pii/S0304885306022694> (accessed 10/11/2021).
- (8) Sakon, T.; Adachi, Y.; Kanomata, T. *Metals* **2013**, *3*, 202–224, ISSN: 2075-4701, DOI: 10.3390/met3020202, <http://www.mdpi.com/2075-4701/3/2/202> (accessed 10/11/2021).
- (9) Heczko, O.; Kopecky, V.; Fekete, L.; Jurek, K.; Kopecek, J.; Straka, L.; Seiner, H. *IEEE Transactions on Magnetics* **2015**, *51*, 1–4, ISSN: 0018-9464, 1941-0069, DOI: 10.1109/TMAG.2015.2453054, <http://ieeexplore.ieee.org/document/7150406/> (accessed 10/11/2021).
- (10) Heczko, O. *Materials Science and Technology* **2014**, *30*, 1559–1578, ISSN: 0267-0836, 1743-2847, DOI: 10.1179/1743284714Y.0000000599, <http://www.tandfonline.com/doi/full/10.1179/1743284714Y.0000000599> (accessed 10/11/2021).
- (11) Heczko, O.; Veřtát, P.; Vronka, M.; Kopecky, V.; Perevertov, O. *Shape Memory and Superelasticity* **2016**, *2*, 272–280, ISSN: 2199-384X, 2199-3858, DOI: 10.1007/s40830-016-0077-9, <http://link.springer.com/10.1007/s40830-016-0077-9> (accessed 10/11/2021).
- (12) Likhachev, A.; Ullakko, K. *Physics Letters A* **2000**, *275*, 142–151, ISSN: 03759601, DOI: 10.1016/S0375-9601(00)00561-2, <https://linkinghub.elsevier.com/retrieve/pii/S0375960100005612> (accessed 10/11/2021).

- (13) Likhachev, A.; Ullakko, K. *The European Physical Journal B* **2000**, *14*, 263–267, ISSN: 1434-6028, DOI: 10.1007/s100510050128, <http://link.springer.com/10.1007/s100510050128> (accessed 10/11/2021).
- (14) Straka, L.; Sozinov, A.; Drahokoupil, J.; Kopecký, V.; Hänninen, H.; Heczko, O. *Journal of Applied Physics* **2013**, *114*, 063504, ISSN: 0021-8979, 1089-7550, DOI: 10.1063/1.4817717, <http://aip.scitation.org/doi/10.1063/1.4817717> (accessed 10/11/2021).
- (15) Aharoni, A.; Pust, L.; Kief, M. *Journal of Applied Physics* **2000**, *87*, 6564–6566, ISSN: 0021-8979, 1089-7550, DOI: 10.1063/1.372771, <http://aip.scitation.org/doi/10.1063/1.372771> (accessed 10/11/2021).
- (16) Kopecký, V.; Perevertov, O.; Straka, L.; Ševčík, M.; Heczko, O. *Acta Physica Polonica A* **2015**, *128*, 754–758, ISSN: 0587-4246, 1898-794X, DOI: 10.12693/APhysPolA.128.754, <http://przyrbwn.icm.edu.pl/APP/PDF/128/a128z4p68.pdf> (accessed 10/11/2021).
- (17) Heczko, O.; Vokoun, D.; Kopecky, V.; Beleggia, M. *IEEE Magnetics Letters* **2015**, *6*, 1–4, ISSN: 1949-307X, 1949-3088, DOI: 10.1109/LMAG.2015.2449252, <https://ieeexplore.ieee.org/document/7132713/> (accessed 10/11/2021).