21st European Conference on Fracture, ECF21, 20-24 June 2016, Catania, Italy

Effect of thermal treatments in Ni-Fe-Ga with Co substitutions and Ni-Mn-Ga melt spun ribbons

F. Tolea*, M. Sofronie, A. D. Crisan, B. Popescu, M. Tolea, M. Valeanu

National Institute of Materials Physics, POB MG-7, 77125 Bucharest-Magurele, Romania

Abstract

The effect of “in situ” thermal treatments (by DSC measurements) on the martensitic transformation in two representative Ni-Fe-Ga and Ni-Mn-Ga alloys has been studied and discussed by correlating the structural and magnetic properties. The alloys were prepared from high purity elements, by arc melting under argon protective atmosphere as bulk and also as melt-spun ribbons - an alternative preparation route that also allows to assess the influences of grains size and strain induced by this processing method. All samples presented reversible thermo-elastic transformations. The thermal treatments promote a reduction of the martensitic transformation temperatures in the Ni-Fe-Ga investigated samples, as opposed to the stoichiometric Ni2MnGa where the temperatures increase with increasing the annealing temperatures. Interestingly however, the off-stoichiometric Ni-Mn-Ga with increased Ni content recovers the behaviour with reduction of transformation temperatures by thermal treatments. The precipitation of the secondary FCC (γ) phase is inherently found in Ni-Fe-Ga alloys with Ga ≤ 27% at, and also -although in lower amounts- in the off-stoichiometric Ni-Mn-Ga. The γ phase is considered to contribute to the decrease of the MT temperatures (via valence electrons concentration depletion of the main matrix) and of the transformation heat as well as to the final structural degradation if the temperature of the thermal treatments is further increased. In addition, this phase, located mainly at the grain boundaries, is responsible for the improved ductility of Ni-Fe-Ga based alloys. Changes in the transformation heat due to thermal treatments are observed and discussed in both types of alloys, the maxima of the transformation heat being associated with the highest atomic order. Thermo-magnetic measurements show that Ni-Fe-Ga alloys have close magnetic and structural transitions temperatures, with promising applications for magnetic refrigeration.

© 2016 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the Scientific Committee of ECF21.

* Corresponding author. Tel.: +0-000-000-0000 ; fax: +0-000-000-0000 .
E-mail address: felicia.tolea@infim.ro

2452-3216 © 2016 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the Scientific Committee of ECF21.
1. Introduction

Usual applications of the Ferromagnetic Shape Memory Alloys (FSMA) are related to a first order phase transition occurring in magnetically ordered domains and well known as the martensitic transformation (MT). For Heusler type FSMA, the transition takes place between austenite (with B2 or ordered L2₁ structure) and either a seven-layer (14M), a five-layer (10M) modulated or a non-modulated (L1₀ tetragonal) martensite structure, depending on the composition and thermal history.

One of the most studied and most promising FSMA is Ni-Mn-Ga, however its brittleness in practical applications encouraged the search for alternatives, such as Ni-Fe-Ga, with improved ductility mainly attributed to the precipitation of a secondary γ phase, situated at the grain boundaries and which favors the inter-granular cohesion.

It is generally accepted that the MT temperatures are correlated with the electron concentration (e/a) but many reports highlighted a large number of other parameters that might influence the transformation, as for example the processing route [Qian, et al. (2011)], chemical and atomic order, internal stress [Hamilton, et al. (2006)] or thermal treatments. Previous reports concerning the influence of the thermal treatments (TTs) on the MT, performed on melt ingots of Ni-Fe-Ga based FSMA with different compositions, concluded that the austenite is more stable and the MT temperature is decreasing by increasing the degree of atomic order [Picornell, et al. (2008); Santamarta et al. (2006)]. By contrary, similar studies performed on Ni-Mn-Ga alloys not far from the stoichiometric composition and without other secondary phases (like γ FCC), show the increase of the MT as long as the atomic order degree increases [Sánchez-Alarcos et al. (2011), Seguí and Cesari (2011)]. Recently reported data have shown that suitable quenching preparation techniques, like melt spinning, may prevent the formation of the secondary γ phase even for the Ni-Fe-Ga based alloys with relative low Ga content (<27%at) [Liu et al. (2003); Okumura and Uemura (2010)]. To note in this context that rapidly quenched ribbons as well as thin films, with tailored MT and Curie temperatures may offer new opportunities for applications as miniaturized active elements for sensors, actuators and other functional devices. To our knowledge, there is missing data concerning the thermal stability and the effect of TTs on the MT temperatures of Ni-Fe-Ga based alloys as rapidly quenched ribbons, which justifies the present study. Data available on this subject refer to the effect of high temperature treatments in the range of order-disorder (L2₁- B2) transformation [Liu et al. (2004)], mentioning the formation of a pure gamma phase after a long treatment at 1000°C.

The present work investigates the thermal stability and the effect of TTs on the MT in Ni-Fe-Ga alloys with low (≤ 26at %) and one with high (=28at %) Ga content, with or without Co substitution, comparatively with the stoichiometric Ni₅₀Mn₂₅Ga₂₅ and the non-stoichiometric Ni₅₇.₂₅Mn₂₂.₅Ga₂₀.₅, with low Ga concentration. The samples are prepared as ribbons by using the melt spinning method. It is to note the reasoning for the selected alloys compositions: (i) the alloys with low Ga content (≤ 26/at %) are difficult to be obtained as single-phase by normal melting route and the Co addition favors the formation of the FCC phase (ii) on the contrary, alloys with higher Ga content (e.g. 28at %) may be obtained as single phase in melt ingot by subsequent TTs [Liu et al. (2008); Oikawa et al. (2007)].

The data presented in this paper is complementary to previous studies which mainly addressed the effect of heat treatments on bulk Ni-Fe-Ga type alloys [Santamarta et al. (2006), Liu et al. (2008), Picornell, et al. (2008), Santamarta et al. (2006)]. In the mentioned studies, heat treatments were applied to the melt ingots after they have been subjected to initial treatments concerning homogenization (~1000 °C) and atomic ordering (~500 °C). While some of the processes occurring during the TTs on the as-prepared ribbons -the subject of our study - might be similar to those appearing in bulk alloys, the involved mechanisms seem to be different, as shall be emphasized.

2. Experimental

The alloys with nominal composition and related labeling Ni₅₃Co₂Fe₂₀Ga₂₅ (Ga25), Ni₅₃Co₂Fe₂₀Ga₂₆ (Ga26), Ni₅₂Fe₁₆Ga₂₈ (Ga28), and, respectively, Ni₅₀Mn₂₅Ga₂₅ (Ni50Mn25) and Ni₅₇.₂₅Mn₂₂.₅Ga₂₀.₅ (Ni57Mn22), have been
prepared from high-purity elements by arc melting in argon atmosphere. The ingots were inductively melted in quartz tubes under argon atmosphere and then rapidly quenched by melt spinning technique. Ribbons of about 30 µm thickness and 2-3 mm width were obtained on a rotating copper wheel (linear velocity of 20 m/s, 50 kPa Ar overpressure and crucible with nozzle diameter of 0.5 mm). The crystalline structure was investigated by X-ray diffraction using a Bruker D8 Advance diffractometer (Cu Kα radiation). The microstructure was investigated by Scanning Electron Microscopy (SEM) via a Zeiss Evo 50XVP device. The compositions of ribbons, as checked by energy dispersive X-ray spectroscopy, were the nominal ones, within the limits of the method accuracy. The phase transformation temperatures for as-quenched (AQ) ribbons and after in situ thermal treatments, were determined by differential scanning calorimetry (DSC) via a Netsch Differential Scanning Calorimeter with a scanning rate of 20 K/min. For the in situ measurements of initially AQ melt spun ribbons, each heating or cooling scan was followed by isotherms of 15 minutes. To highlight the order - disorder transition in NiMnGa, we used a Setaram DTA/DSC Thermogravimeter with a scanning rate of 5 K/min in protected atmosphere. The low temperature magnetic measurements were performed with a SQUID (Quantum Design) magnetometer, while the high temperature ones with PPMS (Quantum Design) in the VSM mode.

3. Results and discussions.

3.1 Calorimetric results.

For a deeper understanding of the effects of heating on the MT, calorimetric scans were performed in situ, on the as quenched (AQ) ribbons. The measurements consist of thermal cycles through the MT, each cycle being done to a progressively higher temperature, so that the scans themselves play also the role of repeated thermal treatments (TTs) done up to a (high enough) temperature at which the MT is no more observed by DSC.

![DSC scans](image)

Fig. 1: The in situ DSC scans of a) Ga26, b) Ni50Mn25 and c) (insert) Ni57Mn22 on cooling/heating registered at progressively higher temperatures. c) Heating Ni50Mn22 and Ni57Mn22 up to 1100 °C evidences the order – disorder (L2₁-B2) transition.

In situ DSC scans on all Ni-Fe-Ga alloys evidence a decreasing of the MT temperatures with the increase of the thermal treatment temperature. Fig. 1a, for instance, shows the effect of progressive TTs on the alloy labeled Ga26, with the maximum temperature reached by each DSC scan increasing from 100°C to 550°C. One can notice the progressive decrease of the transformation temperatures, the reaching of a maxima for the transformation heat – for about 200°C TT –, and finally the structure degradation for TT of the order of 550°C. The same behavior is found for the Ga25 and Ga28 alloys (not shown).

On the contrary, similar DSC scans performed on stoichiometric Ni₅₀Mn₂₅Ga₂₅ alloy (Fig. 1b), show the increase of the MT if the temperature of TTs increases [Recarte et al. (2006)], while the reaching of a maxima for the transformation heat and the structural degradation for high TTs are also met in a similar manner for the Ni-Fe-Ga alloys. DSC measurements on Ni₅₇.₂₅Mn₂₂.₅Ga₂₀.₅ (inset of Fig. 1c) show that it is a high temperature shape memory alloy, with decreasing the transformation temperatures by increasing the TT temperature. In this respect, the Ni₅₀Mn₂₅Ga₂₅ and Ni₅₇.₂₅Mn₂₂.₅Ga₂₀.₅ alloys show opposite behavior, which may be related to the order - disorder L₂₁-B₂ transition. According with Maňosa et al. (2003), the phase stability in Ni-Mn-Ga is controlled by the valence electron concentration (average of valence electrons per atom e/a). Thus, stable alloys (with smaller e/a) have the
temperature transition higher than unstable alloys (with higher e/a). As can be seen in Fig.1c, Ni50Mn25 (e/a=7.5) has a higher temperature for L2₁- B2 transition as compared to the Ni57Mn22 alloy (e/a=7.9). Moreover, the transition order/disorder occurs gradually over a very wide temperature range and it is very close to the final austenite temperature, which explains the structural degradation induced by repeated heat treatments.

Fig. 2 shows the modifications of the MT characteristics (obtained from DSC measurements) during the thermal cycles. The evolutions of the forward austenite to martensite peak (T_{Mp}) and reverse peak (T_{Ap}) (Fig. 2a) as well as the mean value of the transformation heat (calculated as average between the forward and reverse transformation) (Fig. 2b) are plotted as a function of the upper limit temperature attained in each cycle.

Thermal cycles performed on Ga25, Ga26 and Ga28 samples up to 200-250°C cause a relative important decrease of the MT temperatures for all the studied alloys; this decrease is attributed to lattice relaxation by the attenuation of the quenched-in strains stored in ribbons during the processing route. [Tolea et al. (2015)]. Further thermal cycles up to 450°C do not change the MT temperatures but the heat of transformation reaches the maximum values, indicating the range of increasing atomic ordering. At these temperatures the atomic mobility is high enough to initiate the diffusion responsible for the B2-L2₁ (disordered-ordered) transition. Then, by cycling up to temperatures higher than 450°C, it begins to decrease, as effect of alloy degradation. However, even for the alloy with high Ga content, the structure degradation begins in the same temperature range as for those with low Ga content. According with Sánchez-Alarcos et al. (2011) and Seguí and Cesari (2011), DSC scans performed on stoichiometric Ni₅₀Mn₂₅Ga₂₅ alloys show the increase of the MT temperatures as long as the atomic order degree increases. The behaviour of the transformation heat of Ni₅₀Mn₂₅ alloy, until 200°C, suggests that, besides the expected relaxation of the quenched-in strains stored in ribbons via melt-spinning preparation route, an order-disorder competition also takes place. Even after the heat of transformation reaches its maxima, the corresponding martensitic transformation temperatures continue to rise, despite structural degradation indicated by the decrease heat transformation. In situ high temperature TTs on the Ni₅₇Mn₂₂ alloy concomitantly induce the decrease of the MT temperatures and of the transformation heat. It is worth mentioning that the thermal hysteresis (T_{Ap}- T_{Mp}) is almost constant up to the temperature at which the heat of transformation begins to fall consistently to zero.

The thermal stability of the AQ Ga25 ribbons was checked by 20 repeated DSC runs in two temperature ranges: room temperature up to 250°C and up to 500°C (Fig 2c). The ribbons show a high stability after 20 heating – cooling cycles up to 250°C – see the inset Fig. 2c. Neither the MT temperatures, nor the transformation heat change are consistent with the reported behavior of the bulk alloys [Santamarta et al. (2006)]. On the contrary, the thermal scans up to 500°C promote a progressive reduction of MT temperatures and of the transformation heat proving the alloy structure degradation.

3.2 Structure and morphology

The X-ray diffraction (XRD) patterns registered at room temperature on Ni-Fe-Ga as-quenched ribbons, and on
the ribbons subjected to successive “in situ” thermal cycles up to the temperature at which the MT was no more observed by DSC, are shown in Fig. 3a, for Ga25, Ga26 and Ga28 studied samples. The first observation is the missing of the secondary $\gamma$ phase in the pattern recorded on the AQ ribbons of the all alloys. In concordance with the DSC results, Ga25 and Ga28 as prepared ribbons are, at room temperature, in martensite phase and the main reflections may be indexed as a modulated 7M type orthorhombic structure. The as prepared state for Ga26 is characterized by the coexistence of the martensite phase with the same orthorhombic structure and the austenite phase with disordered B2 cubic structure. It is to note that the XRD patterns were recorded on the ribbons free sides and not on the sides in direct contact to the wheel surface, during the melt spinning process. However, due to the different cooling velocity between the contact side and the free side a high texture is generally (usually) developed on ribbons [Okumura et al. (2010); Wang et al. (2013)]. For Ga26 the texture is marked by the enhanced intensity of austenite [200] and [400] reflections while for the ribbons in martensite state, the [004] reflection is enhanced.

Fig.3 a) The X-ray diffraction patterns registered at room temperature for Ga26 and Ga28 alloys on AQ as well as on the ribbons after final DSC scans. b) The XRD patterns at room temperature for Ni50Mn25 on AQ ribbons and Ni57Mn22 alloys on AQ and after final DSC scans.

Almost identical XRD spectra were obtained on the ribbons subjected to in situ repeated thermal cycles. The reflections peaks are indexed as belonging to the $\gamma$ phase and to austenite with B2 structure. However, the large broadening of the peaks suggests the reduction of the crystallite size. This may be due to the intra-granular $\gamma$ phase precipitates reducing the size of the transformable phase in the grains, as also observed in the case of bulk alloys [Masdeu et al. (2008)]. As is revealed in Fig.3b, Ni50Mn25 sample show reflection peaks of L2$_1$ austenite structure. Ni57Mn22 sample is at RT in the martensite phase with 7M tetragonal modulated structure. After DSC “in situ” progressive treatments, $\gamma$ phase precipitated Ni57Mn22 and the peaks become larger, so repeated DSC scans produce an important decrease of the crystallite size.

Specific morphologies as evidenced by SEM on AQ ribbons as well as on thermally treated ribbons are shown in Fig. 4. At RT martensite and austenite states coexists on the Ga26 AQ ribbons. Accordingly, the microstructure shows variants of the twinned martensite (Fig 4a). The textured structure observed by XRD is now proven by the SEM images on the fractured cross section of the as prepared Ga26 ribbons (Fig 4d insert). Due to the gradient of cooling rate across the ribbon, the grains placed on the contact side (bottom of the inset figure) are small and equiaxial whereas columnar grains grow upward to the free surface. A dramatic change induced by the repeated thermal treatments on the microstructure is observed on Ga26. For this alloy, the last observed reverse transformation is well below room temperature so that Fig. 4b shows the austenite microstructure in the last stage of the MT degradation, the high density of cracks gives an aspect of porous material that was also suggested by the brittleness of the ribbons and which could be seen also in fracture (Fig.4e).

SEM images on Ni57Mn22 (Fig. 4c) emphasize the twinned morphologies of the martensite. After TT (Fig. 4f) voids and cracks give the evidence for the degradation of the microstructure.

### 3.3 Magnetic measurements

This section presents magnetic thermo-measurements on the Ni-Fe-Ga alloys. With respect to the magnetic
behaviour of the as prepared and thermally treated Ga25 ribbons, Fig. 5a shows the temperature dependence of magnetization, measured in low magnetic field. By comparing DSC and thermo-magnetic results, the as prepared Ga25 ribbons exhibit coupled magnetic and structural transitions. Materials with concomitant structural and magnetic transitions are expected to have a large entropy variation and hence, an important magnetocaloric effect. Recent studies [Recarte et al. (2007); Seguí and Cesari (2011)] have shown that the entropy change associated to the MT in FSMA increase as the temperature difference between $T_c$ and $T_M$ decreases. Considering that the melt-spun ribbons can assure a more efficient heat transfer in magnetic cooling devices, due to the lamellar geometry, Ga25 ribbons with the magneto-structural transition at 100°C might be an interesting magneto-refrigeration material.

Fig. 4. SEM images reflecting the evolution of the ribbons surface microstructure: (a) AQ Ga26 ribbons and fractured cross section (d); (b) Ga26 after repeated thermal cycles and fractured cross section (e); (c) AQ Ni57Mn22 ribbons; (f) Ni57Mn22 after repeated thermal cycles.

Fig 5. Thermomagnetic measurements on AQ and after in situ TTs (DSC scans) performed on (a) Ga25 ribbons; in inset is evidenced, correlating with DSC results, the magneto-structural transformation on AQ ribbons; (b) on Ga26 ribbons and (c) Ga28.

The thermo-magnetic measurements performed on Ga26 ribbons show the effect of TTs on the magnetic and martensitic transformation (Fig. 5b). Repeated in situ TT induce the precipitation of the secondary $\gamma$ phase which is ferromagnetic with $T_c > 125^\circ$C. This new phase depletes the matrix in 3d-elements and consequently, leads to the reduction of the exchange interactions and of the electron concentration ratio (e/a) and implicitly of $T_M$ and $T_c$ for the
martensite phase. Surprisingly, but also attesting the accuracy of the magnetic measurements, the thermomagnetic measurements reveal the martensitic transformation even on the ribbons subjected to in situ DSC scans. The very large thermal hysteresis, obtained for Ga25 and Ga26 samples after DSC scans extended over 100°C, may be due to precipitation of secondary phases, compositional inhomogeneity or crystallite size reduction. Such large thermal hysteresis may explain also why the transformation was not observed by DSC. The magnetization thermal variation for Ga28 ribbons (Fig. 5c) reveals a ferromagnetic behaviour with a Curie temperature of -30°C, well below the MT temperature, and thus, Ga28 is certainly a simple shape memory alloy and not a FSMA, similar to the case of the bulk alloy [Oikawa et al. (2007)].

4. Conclusions

The effect of thermal treatments on the MT of melt spun ribbons of Ni-Fe-Ga alloys with Co substitutions and Ni-Mn-Ga alloys with different Ga concentrations have been analysed by calorimetric, XRD, SEM and magnetic measurements. The as prepared ribbons are single phase – even for low Ga concentration- and present high atomic disorder and large strains, as characteristic features induced by the processing route. All samples presented reversible thermo-elastic transformations.

In situ TTs promote specific changes on the MTs, in regard to both the transition temperature and transformation heat. On the Ni-Fe-Ga alloys, TTs initiate three distinct mechanisms: (i) in the low temperature range, 200-250°C, the large strains induced by the processing route are relaxed leading to an abrupt decrease of the MT temperature and to an enhancement of the transformation heat; (ii) TTs performed up to 400-450°C bring no variation or a slow reduction of the MT temperatures, due to increased atomic ordering. In this case the duration of TT is an important parameter because diffusion – responsible for atomic ordering – is a time consuming process. (iii) TTs at temperatures higher than ~450°C promote the morpho-structural degradation of the ribbons and as consequence, a fast decrease of both the transformation heat and temperature. The segregation and growth of a secondary γ phase on the account of the main transformable phase is considered to contribute essentially to the decrease of the MT temperature (via the depletion of the main phase in valence electrons) and of the transformation heat as well as to the final structural degradation.

The process (i) is rather specific to melt-spun ribbons due to the strains embedded in the matrix by the rapid cooling velocity. The properties (ii) and (iii), in direct connection to homogenization and atomic ordering processes, are also common for the bulk alloys. Interestingly however, DSC scans performed on stoichiometric Ni-Mn-Ga alloy show an opposite behavior than (ii), namely the increase of the MT as long as the atomic order degree increases [Sánchez-Alarcos et al. (2011); Segui and Cesari (2011)], while in the non-stoichiometric Ni57Mn22 alloy, the MT temperatures again decreases with increase of the temperatures of treatments and the secondary γ phase segregate and the property (iii) is respected. From these one can conclude that the property (iii) is may be related to the segregation of the γ phase.

The transformation temperatures vary consistently in ribbons with low Ga content exposed to TTs. Such variations are more pronounced compared to the bulk alloys, offering new possibilities to tune the MT temperatures by adequate TTs. The magneto-structural transition evidenced on as prepared Ga25 ribbons at ~100°C recommends this alloy as a promising magneto-refrigerator material.

Acknowledgements

This work was supported by grants of the Romanian Ministry of National Education, CNCS – UEFISCDI, project number PN-II-ID-PCE-2012-4-0516, and by the Core Program 2016-2017.

References

Oikawa K., Ota Y., Ohnori T., Tanaka Y., Morito H., Kainuma R., Fukamichi K., Ishida K., 2002. Magnetic and martensitic phase transitions in ferromagnetic Ni–Ga–Fe shape memory alloys. Applied Physics Letters 81, 5201.
Qian J. F., Liu E.K., Feng L., Zhu W., Li G.J., Wang W.H., Wu G.H., Du Z.W., Fu X., 2011. Unusual magnetic anisotropy in the ferromagnetic shape-memory alloy Ni$_{50}$Fe$_{23}$Ga$_{27}$. Applied Physics Letters 99, 252504.
Hamilton R.F., Efstrathiou C., Sehitoglu H., Chumlyakov Y., 2006. Thermal and stress-induced martensitic transformations in NiFeGa single
crystals under tension and compression. Scripta Materialia 54, 465-469.
Picornell C., Pons J., Cesari E., Dutkiewicz J., 2008. Thermal characteristics of NiFeGaMn and NiFeGaCo ferromagnetic shape memory alloys. Intermetallics 16, 751-757.
Santamarta R., Cesari E., Font J., Muntasell J., Pons J., Dutkiewicz J., 2006. Effect of atomic order on the martensitic transformation of Ni-Fe-Ga alloys. Scripta Materialia 54 1985-1989.
Sánchez-Alarcos V., Pérez-Landazábal J.I., Recarte V., 2011. Influence of long-range atomic order on the structural and magnetic properties of Ni-Mn-Ga ferromagnetic shape memory alloys. Materials Science Forum 684, 85.
Seguí C., Cesari E., 2011. Effect of ageing on the structural and magnetic transformations and the related entropy change in a Ni–Co–Mn–Ga ferromagnetic shape memory alloy. Intermetallics 19, 721-725.
Liu Z.H., Zhang M., Cui Y. T., Zhou Y. Q., Wang W. H., Wu G. H., Zhang X. X., Xiao G., 2003. Martensitic transformation and shape memory effect in ferromagnetic Heusler alloy NiFeGa. Applied Physics Letters 82, 424.
Okamura H., Uemura K., 2010. Influence of quenching rate on the magnetic and martensitic properties of Fe–Ga melt-spun ribbons. Journal of Applied Physics 108, 043910.
Liu Z. H., Liu H., Zhang X.X., Zhang M., Dai X.F., Hu H.N., Chen J.L., Wu G.H.,2004. Martensitic transformation and magnetic properties of Heusler alloy Ni-Fe-Ga ribbon. Physics Letter A 329, 214-220.
Liu J., Scheerbaum N., Hinz D., Gutfleisch O., 2008. Martensitic transformation and magnetic properties in Ni-Fe-Ga-Co magnetic shape memory alloys. Acta Materialia 56, 3177-3186.
Okawa K., Omori T., Sutou Y., Morito H., Kainuma R., Ishida K., 2007. Phase equilibria and phase transition of the Ni-Fe-Ga ferromagnetic shape memory alloy system. Metallurgical and Materials Transactions A, 38A, 767-776.
Santamarta R., Font J., Muntasell J., Masdeu F., Cesari E., Dutkiewicz J., 2006. Effect of ageing on the martensitic transformation of Ni-Fe-Ga alloys. Scripta Materialia 54, 1105-1109.
Recarte V., Pérez-Landazábal J.I., Gomez-Polo C., Seguí C., Cesari E., Ochin P., 2006. High temperature rearrangements in melt-spun NiMnGa ribbons. Materials Science and Engineering A 438-440, 927-930.
Mohana L., Planes A., Acet M., Duran E., Wassermann E.F., 2003. Magnetic properties and martensitic transition in annealed Ni50Mn30Al20. Journal of Applied Physics 93, 8498.
Tolea F., Sofronie M., Crisan A.D., Enculescu M., Kunser V., Valeanu M., 2015. Effect of thermal treatments on the structural and magnetic transitions in melt-spun Ni-Fe-Ga-(Co) ribbons. Journal of Alloys and Compounds 650, 664-670.
Wang J., Jiang C., Tachapiesancharoenkij R., Bono D., Allen S.M., O’Handley R.C., 2013. Microstructure and magnetic properties of melt spinning Ni-Mn-Ga. Intermetallics 32, 151-155.
Masdeu F., Pons J., Santamarta R., Cesari E., Dutkiewicz J., 2008. Effect of precipitates on the stress-strain behavior under compression in polycrystalline Ni-Fe-Ga alloys. Materials Science and Engineering: A 481-482, 101-104.
Recarte V., Perez-Landazabal J.I., Gomez-Polo C., Cesari E., Dutkiewicz J., 2007. Magnetocaloric effect linked to structural and magnetic transitions in Ni-Fe-Ga alloys. Journal of Magnetism and Magnetic Materials 310, e999-e1001.