Fine Particle Morphology and Superparamagnetic Property of Overaged Fe-Al-Mn-C Alloys

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This investigation reports on a scanning electron microscopy (SEM) and transmission electron microscopy (TEM) study of fine particle morphologies formed in Fe-9Al-xMn-y (C, Si) alloys overaged at 823 K from 13 h to 120 d. The results reveal that the fine particle morphologies come from the lamellar structures due to a phase transformation. Two structures are contained in the fine particle morphologies, one is the ordered B2 phase with monoclinic α' Mn structure, the other is the ferromagnetic spinel ordered (B2+D0₃) structures precipitated from the (γ + κ) matrix. A superparamagnetic behaviour was discovered, as the alloy overaged at 823 K for 120 d. The super soft magnetic property of the specimen is mainly attributable to the fine particle morphologies, which consist of the ferromagnetic spinel ordered (B2+D0₃) phases and ordered B2 with monoclinic α' Mn structures.

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I. Introduction

Intermetallic compounds with useful physical properties lead to the development of functional materials as superconductors based on Nb₃Sn compounds, shape-memory alloys (NiTi), high permeability magnetic materials (Ni₃Fe) and permanent magnet alloys (Co₅Sm)⁽¹⁾⁽²⁾. Intermetallics crystallize in structures with ordered atom distributions in which atoms are preferentially surrounded by unlike atoms. Atom diffusion in an intermetallic compound is not through random vacancy motion, but through the complicated ordering atom nearest-neighbour (NN) jump sequences on its own sublattice without disturbing the ordered arrangement of atoms on lattice sites⁽³⁾⁻⁽⁵⁾. NN was connected with 1/4 $a_0\langle 111 \rangle$ antiphase boundary segments (APBs) of D0₃ or equivalent to the 1/2 $a_0\langle 111 \rangle$ APBs of B2.

By means of a proper alloy designing and overaging at 823 K for 120 d, the alloy Fe-9Al-xMn-y (C, Si) will give rise to secondary fine-grain particle morphologies⁽⁶⁾, which are intermetallic compounds. From the measurement of the magnetic properties, it reveals that a super soft magnetic property (similar to superparamagnetism) exists in the alloy overaged at 823 K for 120 d. According to Cullity's postulation, the super soft magnetic property of the alloy overaged at 823 K for 120 d is mainly ascribed to the fine particle morphologies⁽⁷⁾. In an attempt to characterize the soft magnetic phases in exhibition in the fine particle morphologies, the specimen overaged at 823 K for 120 d was examined using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). This paper presents the results of a SEM and TEM investigation of phase relations and microstructures in the fine particle morphologies. The

results reveal that the fine particle morphologies are comprised of; (a) an ordered AB compound B2 [(Fe/Mn)Al] phase, (b) an ordered A₃B compound D0₃ [(Fe/Mn)₃Al] phase, (c) an α' Mn monoclinic structure and (d) the (γ + κ) phases. In addition, the monoclinic α' Mn phase transformation from the ordered B2 phase; the ferromagnetic spinel ordered (B2+D0₃) precipitation from along a direction at nearly 45° from the (γ + κ) matrix; the ferromagnetic spinel morphology preferentially developing along the set of NN direction—the 1/2 $a_0\langle 111 \rangle$ APBs of B2 (or 1/4 $a_0\langle 111 \rangle$ APBs of D0₃), will be confirmed in this paper using TEM.

II. Experimental Procedure

The alloy was made by melting the electrolytic iron (99.9%), electrolytic manganese (99.9%), high-purity aluminum (99.99%), high-purity carbon and silicon in a vacuum induction furnace under a controlled protective argon atmosphere. The cast ingot was homogenized at 1473 K for 12 h under a protective argon atmosphere, then hot forged and cold-rolled to a thickness of 1.2 mm. The specimens were cut to the same size of 1.2 mm × 30 mm × 60 mm, then subsequently solution treated at 1323 K for 1 h and rapidly quenched into water at room temperature. Overaging treatment was carried out at 823 K from 13 h to 120 d. The thin foil specimens for TEM were prepared by double jet electropolishing in a solution containing 10% perchloric acid and 90% acetic acid at a temperature in the range 10°C to -7°C using a current density of 5 kA/m²-18 kA/m². Transmission electron microscopy was performed by a JEOL 2000 Fx, with a double-tilt stage operated at 200 kV and a Philips 400 ST at 120 kV. The scanning electron microscopy (SEM) study was carried out using an AKASHI X-40 operated

at 20 kV. The magnetic property measurements were carried out with an Oxford Instruments (Aerosonic 3001) vibrating sample magnetometer (VSM) with autocompensation magnetic scales, and tested at room temperature. The $M(B)$ - H curve was determined by measuring the AC permeability as a function of applied DC magnetic field with a maximum applied field of 1 T (*i.e.*, 10000 Oe).

III. Results and Discussion

1. SEM observation and analysis

In Figs. 1(a)–(d), the typical lamellae and fine particle morphologies in the alloy overaged at 823 K for 120 d as observed by SEM are shown. The SEM microstructures of the specimen consist of three phases, *i.e.*, the lamellar structures and the fine particle morphologies comprising of porous and spinel structures are indicated by the arrows shown in Fig. 1(a), respectively. Because the lamellar structures are reported elsewhere⁽⁸⁾, this paper will focus on the study of the porous and spinel structures revealed by TEM. The corresponding SEM higher magnification photographs of lamellar, porous, and spinel structures are shown in Figs. 1(b), (c) and (d), respectively.

2. TEM observation and analysis

(1) Fine particle morphologies—the porous structures

Figures 2(a)–(c) are a series TEM photographs taken of the fine particle morphologies' porous structures shown in Figs. 1(a) and (c). For confirmation of the ordered B2 [(Fe/Mn)Al] structure existence in this region, the selected area diffraction pattern (SADP) demonstrates the zone axis of the ordered [012] B2 phase shown in Fig. 2(a), in which the fundamental reflections $h+k+l=2n$ [*i.e.*, (200), (12 $\bar{1}$), . . .] as well as the superlattice reflections $h+k+l=2n+1$ [*i.e.*, (02 $\bar{1}$), (100), (0 $\bar{2}$ 1), . . .] are exposed in this zone axis SADP. Figure 2(b) is the dark field (DF) image using the (200) ordered B2 reflection corresponding to Fig. 2(a). Partially ordered B2 anisotropic antiphase boundary segments (APBs) appear as indicated by the arrows in Figs. 2(b) and (c). The Mn atom concentration at the antiphase boundary segment (APBs) of the ordered B2 phase causes the α' Mn phase (monoclinic structure) to precipitate preferentially along the APBs of the ordered B2 phase, and gives rise to the displacement fringe contrast (lattice-misfit strain) which is very apparent sharply in the ordered B2 dark field image^{(9)–(12)}. Figure 2(c) is the corresponding bright field (BF) image in which the ordered B2 phase and monoclinic α' Mn structure is indicated by the arrows in Fig. 2(c). By careful analysis, the fault fringe contrast revealed in the BF image results in the formation of thin layer precipitation α' Mn phases along the APBs of the ordered B2 structure that will strain the ordered B2 lattice. The Mn atom concentration at the APBs of the ordered B2 phase induces

Fig. 1 Scanning electron microscopy (SEM) photographs of the alloy overaged at 823 K for 120 d, the microstructures of the specimen consist of three phases. (a) lamellae, and the fine particle morphologies comprising of porous and spinel structures. The corresponding higher magnification micrographs show the (b) lamellar, (c) porous and (d) spinel structure, respectively.

Fig. 2 Transmission electron microscopy (TEM) micrographs of the alloy overaged at 823 K for 120 d, taken from the porous structures of the fine particle morphologies, showing they contained B2 [(Fe/Mn)Al] phase. (a) selected area diffraction pattern (SADP) of the zone axis [012] ordered B2 phase, (b) (200) ordered B2 dark field (DF) image revealing anisotropic B2 antiphase boundary segments (APBs), (c) bright field (BF) image.

monoclinic α' Mn structure development preferentially along the APBs of the ordered B2 [(Fe/Mn)Al] phase, which will be coincident with the next series of TEM photographs as observed in the present work^{(9)–(12)}. Figure 3(a) is the zone axis of ordered B2 $[\bar{1}13]$ SADP taken from same region, for which all the reflections are imaged to be $h+k+l=2n$ for the fundamental reflections of the ordered B2 phase. The dark field image using the $(\bar{1}\bar{1}0)$ ordered B2 fundamental reflection corresponding to Fig. 3(a) is shown in Fig. 3(b). The asymmetric fault fringes existence in the dark field image of the $(\bar{1}\bar{1}0)$ ordered B2 fundamental reflection is confirmed by the displacement fringe contrast arising from a thin precipitate^{(9)–(12)}. The corresponding $(\bar{1}\bar{1}0)$ ordered B2 bright field image is shown in Fig. 3(c) revealing symmetric fault fringes⁽¹²⁾. By careful examination of Figs. 2 and 3, the ordered B2 phase seems to be a porous intermetallic compound in which the monoclinic α' Mn structure precipitates from the APBs of the ordered B2 phase, and the ordered B2 phase surrounds the monoclinic α' Mn structure as well. To verify the nature of the ordered B2 phase contained within the porous morphologies, a typi-

cal SADP of the [001] ordered B2 zone axis is shown in Fig. 3(d) which was obtained from the same region by carefully tilting the specimen.

After properly tilting the specimen and observing the same region, a different SADP is obtained as shown in Fig. 4(a). The crystallographic normal demonstrates the monoclinic $[\bar{1}\bar{1}0]$ α' Mn zone axis. The monoclinic α' Mn phase has lattice parameters of $a=0.66$ nm, $b=0.79$ nm, $c=0.64$ nm, and $\beta=109.4^\circ$. Figure 4(b) is the dark field image using the $(00\bar{3})$ monoclinic α' Mn reflection corresponding to Fig. 4(a). From the DF image analysis, δ -fringe layers exist in the monoclinic α' Mn phase⁽¹³⁾⁽¹⁴⁾. The monoclinic α' Mn phase is also surrounded by the ordered B2 phase as revealed in this DF image. Corresponding BF image shown in Fig. 4(c), the monoclinic α' Mn phase transforms from the ordered B2 phase that the fault fringes and antiphase boundary segments (APBs) exist in the ordered B2 phase indicated by the arrows. For further confirmation of identification of the fine particle monoclinic α' Mn phase, the other SADPs are taken from the same region and are shown in Figs. 4(d)–(f), in which the zone axes of monoclinic α' Mn

Fig. 3 TEM micrographs of the same specimen are taken from the porous structures which consist of the ordered B2 phase. (a) selected area diffraction pattern of the $[113]$ ordered B2 zone axis, (b) $[110]$ ordered B2 dark field image with asymmetric fault fringes, (c) $[110]$ ordered B2 bright field image with symmetric fault fringes, (d) zone axis of the $[001]$ ordered B2 phase.

structure analysed are $[01\bar{3}]$, $[3\bar{1}\bar{1}]$ and $[0\bar{2}1]$, respectively.

Taken from the same specimen, a SADP including the monoclinic α' Mn structure and ordered B2 phase is shown in Fig. 5(a), for which the crystallographic orientation relationship between the monoclinic α' Mn structure and the ordered B2 phase is $[0\bar{6}2]_{\alpha'\text{Mn}} // [023]_{\text{B2}}$. Figure 5(b) is the dark field image formed using the (200) monoclinic α' Mn reflection corresponding to Fig. 5(a). The monoclinic α' Mn phase has a “peanut” shape, characterized by periodic bulges in the δ -fringe layers on the monoclinic α' Mn phase. Figure 5(c) is the dark field image of the fundamental (200) ordered B2 reflection corresponding to Fig. 5(a). The monoclinic α' Mn phase begins to precipitate in regions contiguous to the ordered B2 phase that leads to a displacement fringe contrast and causes a lattice-misfit strain in the ordered B2 phase. Figure 5(d) is the BF image, which shows the fault fringes appearing in the ordered B2 phase⁽¹²⁾. Other SADPs including the monoclinic α' Mn and the ordered B2 phases are shown in Figs. 5(e) and (f), in which the

orientation relationships between the monoclinic α' Mn and the ordered B2 phases are demonstrated to be $[01\bar{3}]_{\alpha'\text{Mn}} // [14\bar{2}]_{\text{B2}}$, and $[01\bar{2}]_{\alpha'\text{Mn}} // [\bar{1}13]_{\text{B2}}$, respectively. Note, as shown in Fig. 5(f) that the SADP of the ordered B2 $[\bar{1}13]$ zone axis is exactly coincident with the SADP of the zone axis $[\bar{1}13]$ ordered B2 structure shown in Fig. 3(a). This indicates that these two analogous ordered B2 $[\bar{1}13]$ SADPs can be regarded as being the same as the ordered B2 phase. Also, as shown in Fig. 5(e), the SADP of the monoclinic α' Mn $[01\bar{3}]$ zone axis is in accurate agreement with the SADP of the zone axis $[01\bar{3}]$ monoclinic α' Mn structure as shown in Fig. 4(d). This result can also be explained by the fact that these two similar monoclinic α' Mn $[01\bar{3}]$ SADPs can be considered as the same as monoclinic α' Mn structure.

(2) Fine particle morphologies—the spinel structures

The second structure present in the fine particle morphologies is the spinel structure. Since the spinel morphology is ferromagnetic^{(7)(15)–(23)}, it is difficult to obtain SADPs of the spinel structures by TEM. The related mag-

Fig. 4 TEM micrographs of same specimen are taken from the porous structure which consist of the monoclinic α' Mn phase. (a) zone axis of $[1\bar{1}0]\alpha'$ Mn phase, monoclinic α' Mn structure has a lattice parameter of $a=0.66$ nm, $b=0.79$ nm, $c=0.64$ nm, and $\beta=109.4^\circ$, (b) DF image using the $(00\bar{3})\alpha'$ Mn reflection corresponding to (a), (c) BF image of α' Mn phase. The other zone axes of the monoclinic α' Mn phase are (d) $[01\bar{3}]$, (e) $[3\bar{1}\bar{1}]$ and (f) $[0\bar{2}1]$, respectively.

netic property will be discussed in Section III-3, and a more detailed research will be reported in the near future. At the moment, the important work is focused on identifying the crystal structure of the spinel morphologies. First, shown in Fig. 6(a) is the typical $[011]_\kappa // [011]_\gamma$ zone axis, which is taken from the spinel structures of the fine particle morphologies as shown in Figs. 1(a) and (d). A dark field image using the $(200)_\kappa$ phase reflection corresponding to Fig. 6(a) is shown in Fig. 6(b). The spinel morphology has the dark contrast

and the bright contrast is the κ -phase precipitated from the γ -matrix. Figure 6(c) is the bright field image revealing a typical spinel morphology apparent in the $(\gamma + \kappa)$ matrix. Note, the magnification of the BF spinel image is smaller. Using careful TEM observation, it was discovered that the κ -phases precipitate along one of the three elastically soft $\langle 100 \rangle$ directions (*i.e.*, the notation $\langle 100 \rangle$ directions mean the set of $[100]$, $[010]$, $[001]$ directions) from the γ -matrix following the ferromagnetic spinel structures precipitating at nearly 45° from the κ -phases,

Fig. 5 TEM micrographs of the alloy overaged at 823 K for 120 d are taken from the porous structures which include the monoclinic α' Mn structure and ordered B2 phase. (a) zone axis of $[0\bar{6}2]_{\alpha'Mn} // [023]_{B2}$, (hkl =monoclinic α' Mn; hkl =ordered B2), (b) (200) monoclinic α' Mn DF image, (c) (200) ordered B2 DF image, (d) BF image of including monoclinic α' Mn and ordered B2 phases. The other zone axes, including the monoclinic α' Mn structure and ordered B2 phase, demonstrate (e) $[01\bar{3}]_{\alpha'Mn} // [1\bar{4}\bar{2}]_{B2}$, and (f) $[01\bar{2}]_{\alpha'Mn} // [\bar{1}13]_{B2}$, respectively.

and the ferromagnetic spinel structures preferentially develop along the set of NN direction—the $1/2 a_0 \langle 111 \rangle$ APBs of B2 (or $1/4 a_0 \langle 111 \rangle$ APBs of $D0_3$). It seems these are the phase transformation mechanism of the ferromagnetic spinel structures from κ -phases. Figure 6(d) is the SADP taken from the ferromagnetic spinel structures with the upper reflection spots due to the zone axis $[\bar{1}33]$ of the ordered B2 phase and the lower reflection spots due to the zone axis $[011]_{D0_3} // [011]_{B2}$ of the ordered (B2+ $D0_3$) structure, respectively. Figure 6(e) is the DF image of $(01\bar{1})$ ordered B2 [or $(02\bar{2})$ ordered $D0_3$] reflec-

tion corresponding to Fig. 6(d), in which the bright spinel contrast is the ordered (B2+ $D0_3$) structure. The ferromagnetic spinel structures observed at both ends of the images become thinner (e.g., needle morphology), indicating dissolution of (Fe/Mn) atoms due to Ostwald ripening. The needle-shape morphology of the ferromagnetic spinel ordered (B2+ $D0_3$) structure gives a hint as to the diffusion-path for Ostwald ripening of plate precipitates⁽¹⁹⁾. The γ , κ and ferromagnetic spinel ordered (B2+ $D0_3$) phases are indicated by the arrows shown in the BF image of Fig. 6(f). By carefully analysing the BF

Fig. 6 TEM micrographs of the alloy overaged at 823 K for 120 d taken from the fine particle morphologies' spinel structures. (a) zone axis of $[011]_{\kappa} // [011]_{\gamma}$, ($hkl = \kappa$ -phase; $hkl = \gamma$ -matrix), (b) $(200)\kappa$ -phase DF image, (c) BF image. Note, for obtaining the much more spinel morphologies, the smaller magnification was taken in the BF image (c), (d) SADP taken from the ferromagnetic spinel structures, upper reflection spots demonstrate the zone axis of $[\bar{1}13]$ ordered B2 phase, lower reflection spots, illustrate the zone axis $[011]_{D0_3} // [011]_{B2}$ of the ordered $(B2 + D0_3)$ structure, ($hkl = D0_3$; $hkl = B2$), (e) $(01\bar{1})$ ordered B2 [or $(02\bar{2})$ ordered $D0_3$] DF image, (f) BF image. Note, a nearly 45° morphological orientation relationship between the ferromagnetic spinel ordered $(B2 + D0_3)$ structures and κ -phases is shown in the BF image (f).

image in Fig. 6(f), it reveals that the perovskite carbide κ -phases $L'1_2$ $[(Fe/Mn)_3AlC]$ precipitate along one of the three elastically soft $\langle 100 \rangle$ directions from the γ -matrix following the ferromagnetic spinel ordered $(B2 + D0_3)$ structures precipitate in a direction of nearly 45° from the κ -phases. The ferromagnetic spinel structures develop preferentially along the set of NN direction—the $1/2 a_0 \langle 111 \rangle$ APBs of B2 (or $1/4 a_0 \langle 111 \rangle$ APBs of $D0_3$) as revealed in the DF and BF images (Figs. 6(e)

and (f)). On the other hand, there is a nearly 45° morphological orientation relationship between the κ -phases and the ferromagnetic spinel ordered $(B2 + D0_3)$ structures, within which the ferromagnetic spinel ordered structures also preferentially develop each other with a nearly 70° – 90° morphological relationship, and the ferromagnetic spinel structures have an ordered B2 and $D0_3$ electron diffraction patterns as shown in Fig. 6(d).

Fig. 7 Mass magnetization (M) versus magnetic field (H) M - H curves measured at room temperature of the alloy overaged at 823 K for (a) 13 h and (b) 120 d, respectively.

3. Magnetic properties

The mass magnetization (M) versus magnetic field strength (H) M - H curves, measured at room temperature, of the alloy overaged at 823 K for 13 h and 120 d is shown in Figs. 7(a) and (b), respectively. The hysteresis loops exhibit soft magnetic behaviour and reveal the magnetization values of the magnetic moment per unit mass are 21 ($\text{A m}^2/\text{kg}$) and 48 ($\text{A m}^2/\text{kg}$), (*i.e.*, $1 \text{ A m}^2/\text{kg} = 1 \text{ emu/g}$). By careful analysis of Figs. 7(a) and (b), the overaged specimens become saturated in a small applied field. This is a typical magnetic soft material as described by Cullity⁽⁷⁾. The lower mass-magnetization as well as the appearance of the hysteresis loop shown in Fig. 7(a) indicates that the specimen overaged at 823 K for 13 h does not have enough thermal energy to reach a complete thermal equilibrium⁽⁷⁾. Figure 7(b) shows the higher mass-magnetization (48 $\text{A m}^2/\text{kg}$) and the very small hysteresis loop (*i.e.*, vanishing of the retentivity and coercivity). This very small hysteresis loss is achieved by the alloy overaged at 823 K for 120 d that induces a precipitation of fine crystallites. These precipitates provide nucleation sites for domain walls, thereby refining the domain structure and reducing the hysteresis losses. One special case in which the details of the magnetization loop can provide considerable metallurgical information is the alloy overaged at 823 K for 120 d containing "superparamagnetic" particles. These are ferromagnetic particles that are sufficiently fine that the assembly is in thermal

equilibrium with an applied field. This yields a non-hysteretic loop. This fact clearly demonstrates the superparamagnetic nature of the alloy overaged at 823 K for 120 d⁽⁷⁾⁽¹⁷⁾⁻⁽²³⁾. Comparing Figs. 7(a) and (b), it reveals that the alloy overaged at 823 K for 120 d possesses a superior ferromagnetism, a higher susceptibility ($\chi = M/H$) and much better soft magnetic property than that of the alloy overaged at 823 K for 13 h. This ferromagnetism results in a net spontaneous magnetization arising from the alignment with net magnetic moments that the spontaneous magnetization is due to electron spin imbalance in their 4f bands⁽⁷⁾ (*i.e.*, the ferromagnetic spinel ordered ($\text{B2} + \text{D0}_3$) phases preferentially generate along a nearest-neighbour (NN) APBs—the $1/4 a_0 \langle 111 \rangle$ APBs of D0_3 or equivalent to the $1/2 a_0 \langle 111 \rangle$ APBs of B2). From the magnetic property study and SEM observation, the alloy clearly reveals that the longer the overaging time (at 823 K), the more fine particle morphologies, and the higher the saturation magnetization is achieved. Thus, the author believes that the alloy overaged at 823 K for a longer time (120 d) induces the fine particle morphologies possessing long range ordered structures, which can be regarded as the existence of large high anisotropy ferromagnetic phases in the fine particle morphologies and that the fine particle morphologies are mainly responsible for the observed ferromagnetism and super soft magnetic property⁽⁷⁾⁽¹⁷⁾⁻⁽²³⁾.

Cullity⁽⁷⁾ has reported that fine particles of magnetic alloys may be prepared by a variety of methods. For example, some alloys can be heat treated in such a way that fine particles of a magnetic phase are precipitated out of a non-magnetic matrix. The precipitation of fine magnetic particles from a non-magnetic matrix may be anisotropic. The presence of these small magnetic particles will reduce eddy current and hysteresis losses, and will produce superparamagnetic behaviour⁽⁷⁾⁽²¹⁾. Accordingly, the result of this study is in agreement with Cullity's postulation. Fine-particle morphologies observed by SEM and TEM indicate that the ferromagnetic spinel ordered ($\text{B2} + \text{D0}_3$) phases and ordered B2 with monoclinic α' Mn structures exist in the fine-particle region. Further, the TEM photographs show that the fine-particle regions are in a matrix of γ (FCC) and κ -phases, which are paramagnetic (*i.e.*, non-magnetic matrix) and the ferromagnetic spinel ordered ($\text{B2} + \text{D0}_3$) phases precipitate with a nearly 45° direction from the κ -phases and preferentially develop along the set of NN direction—the $1/2 a_0 \langle 111 \rangle$ APBs of B2 (or $1/4 a_0 \langle 111 \rangle$ APBs of D0_3). Summarizing the above observations, the author can conclude that the super soft magnetic property of this alloy overaged at 823 K for 120 d is mainly attributable to the fine particle morphologies, which consist of the ferromagnetic spinel ordered ($\text{B2} + \text{D0}_3$) phases and ordered B2 with monoclinic α' Mn structures.

IV. Conclusions

- (1) Two structures are contained in the fine particle morphologies-porous structures and spinel structures.

(2) The porous structures are comprised of ordered B2 phase with monoclinic α' Mn structure. Due to the Mn atom concentration at the APBs of the ordered B2 phase, the monoclinic α' Mn structure precipitates preferentially along the APBs of the ordered B2 phase and causes the displacement fault fringe contrast (lattice-misfit strain) which appears in the ordered B2 phase.

(3) The orientation relationships between the monoclinic α' Mn structure and the ordered B2 phase are determined to be $[0\bar{6}2]_{\alpha'\text{Mn}}//[023]_{\text{B2}}$; $[01\bar{3}]_{\alpha'\text{Mn}}//[\bar{1}\bar{4}2]_{\text{B2}}$; $[01\bar{2}]_{\alpha'\text{Mn}}//[\bar{1}13]_{\text{B2}}$, respectively.

(4) The ferromagnetic spinel morphologies have ordered (B2+D0₃) structures, which precipitate from the κ -phase within a ($\gamma+\kappa$) matrix. A nearly 45° morphological relationship exists between the ferromagnetic spinel structure and κ -phase, and the ferromagnetic spinel ordered (B2+D0₃) morphology preferentially develops along the set of NN direction—the $1/2 a_0\langle 111 \rangle$ APBs of B2 (or $1/4 a_0\langle 111 \rangle$ APBs of D0₃).

(5) The soft magnetic property of the alloy overaged at 823 K for 120 d mainly attributable to the fine particle morphologies which consist of the ferromagnetic spinel ordered (B2+D0₃) phases and ordered B2 with monoclinic α' Mn structures.

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