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Alignment behavior of the primary Al_3Ni phase in Al–Ni alloy under a high magnetic field

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Influences of a high magnetic field on the alignment behavior of the primary Al_3Ni phase in three hypereutectic Al–Ni alloys have been investigated and the results show that the plane alignment perpendicular to the magnetic field has formed under a certain condition. The alignment-influencing factors have been investigated and it is found that the magnetic field intensity, solidification temperature and the alloy composition have played great roles during the alignment process. Indeed, it is observed that under a certain magnetic field intensity there exists a critical solidification temperature, and above this temperature the alignment degree increases with the increase of the solidification temperature, and that under a certain solidification temperature there exists a critical magnetic field intensity, and above this magnetic field intensity the alignment degree increases with the increase of the magnetic field intensity. It has also been found that with the increase in the Ni content of the alloy the alignment degree decreases. By means of XRD and EBSD analysis, the crystal orientation has studied and results show that the $\langle 001 \rangle$ crystal direction of the Al_3Ni crystal orients along the magnetic field and the $\langle 100 \rangle$, $\langle 110 \rangle$ and $\langle 010 \rangle$ crystal directions align perpendicular to the magnetic field. This is discussed based on the magnetocrystalline anisotropy of the Al_3Ni crystal and the rotating alignment of the primary phase under a high magnetic field.

1. Introduction

Recently, owing to the development of the superconducting technology, a high magnetic field with relatively wide space is easy to obtain. By using a high magnetic field, a lot of new phenomena and functions have been found. Therefore, the application of a high magnetic field has attracted much attention in the area of electromagnetic processing of materials. It is well known that a magnetic force is produced under a high magnetic field and the magnetic force has two effects: one is known as the force in which a magnet pulls ferromagnetic and paramagnetic materials and repels diamagnetic ones and the other as the force in which materials are rotated to a magnetic field direction. Since a large number of materials own the magnetocrystalline anisotropy (i.e., the magnetic susceptibility is different in each crystal direction), they may have the possibility to align to a preferred direction. It is well known that the material properties strongly depend on their crystal orientations, controlling of which may provide an improvement of material characteristics. Therefore, the alignment of non-magnetic materials has been examined during several processes such as solidification, electro-deposition, vapor deposition and solid-phase reaction [1–4]. The experimental research works have demonstrated that a high magnetic field presented a significant influence on the solidification of materials. Mikelson and Karklin [5] obtained the aligned solidification structure in Al–Cu and Cd–Zn alloys in a 1.5 T magnetic field. Savitisky et al. [6] found that the MnBi phase in the alloy aligned along the direction of the magnetic field during the solidification of a Bi–Mn alloy in a magnetic field. Rango et al. [7] extended the investigation to the solidification of paramagnetic $YBa_2Cu_3O_7$ material and obtained textured crystal structure in a magnetic field. Katsuki et al. [8] reported that diamagnetic benzophenone crystallized from *n*-hexane, KCl and $BaCl_2$ crystallized from a solution aligned in a 10 T magnetic field. This alignment behavior of the primary phase in hypo- and hypereutectic alloys has been investigated intensively by several researchers [9,10]. Texture crystal growth of Bi-2201 [11] and Bi (Pb)2212 [12] has also been obtained in a high magnetic field. However, few works have investigated experimentally the influencing factors during the alignment of the primary phase under a high magnetic field in detail. Moreover, no works have studied the relation between the crystal orientation and the phase alignment. In our previous

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works [13], the alignment behavior of the primary Al_3Ni phase in the Al–12 wt%Ni alloy during directional solidification has been investigated. This paper extends the work in Ref. [13] and investigates the alignment behavior of the Al_3Ni phase and that the influencing factors during the volume solidification in detail. It has been found that the magnetic intensity, solidification temperature and the alloy composition have played great roles during the alignment process. By means of XRD and EBSD, the crystal orientation has been studied and the results show that the $\langle 001 \rangle$ crystal direction of the Al_3Ni crystal orients along the magnetic field and the $\langle 100 \rangle$, $\langle 110 \rangle$ and $\langle 010 \rangle$ crystal directions orient perpendicular to the magnetic field. This is discussed based on the magnetocrystalline anisotropy of the Al_3Ni crystal and the rotating alignment of the primary phase under a high magnetic field.

2. Experimental procedure

The three hypereutectic Al–Ni alloys with 8, 10 and 12 wt% of nickel used in this study were prepared with high-purity Al (99.99 wt%) and Ni (99.9 wt%) in an induction furnace. The alloy, being put in a high-purity graphite crucible of 10 cm diameter, was heated to 900 °C, magnetically stirred for 0.5 h and poured into a graphite mold to cast specimens with the diameter of 10 mm and length of 30 mm, respectively. The experimental set-up is shown in Fig. 1 and consists of a superconductor magnet, water-cooling cover, heating furnace and controlling temperature system. The superconductor magnet can generate a high magnetic field up to 14 T. The furnace was set in the room bore of the magnet and the temperature in it could reach 1000 °C. A cast specimen with the diameter of 10 mm was enveloped in the tube of high-purity graphite with the inner diameter of 10 mm and length of 30 mm. The samples were heated to a certain temperature and held for 30 min, then cooled at a certain cooling rate below the eutectic point. Fig. 2 shows the phase diagram of the Al–Ni alloy near Al and temperature profiles for the solidification procedure.

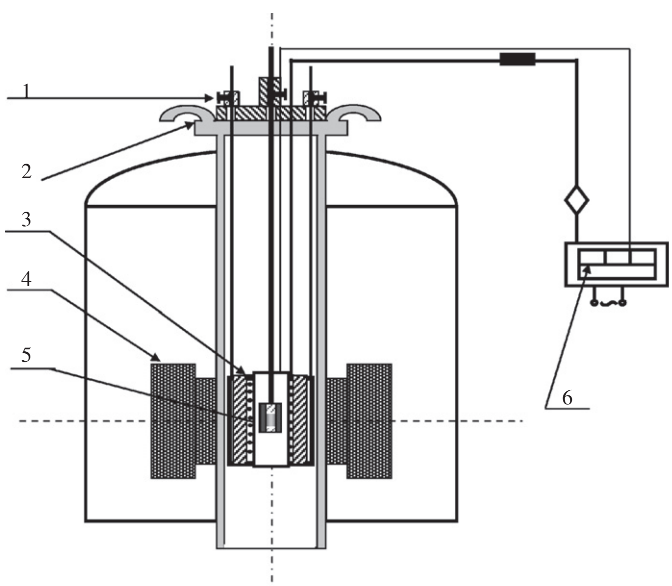

Fig. 1. Schematic of the experimental device for metal solidification under a high magnetic field: 1—sample frame, 2—water-cooling cover, 3—heating furnace, 4—superconductor magnet, 5—sample, 6—controlling temperature system.

The samples obtained from the experiment were cut along the direction parallel and perpendicular to the magnetic field. After machining off the surface, the longitudinal (parallel to the magnetic field direction) and transverse microstructures were examined in the etched condition by an optical microscope and scanning electron microscopy (SEM). Moreover, crystallographic characteristics of the Al_3Ni crystal were investigated by means of the X-ray diffraction (XRD) with Cu–K_α and the electro back-scattered diffraction (EBSD) in a high-resolution scanning electron microscope equipped with a field emission gun (FE-SEM).

3. Results

Fig. 3 shows the microstructures of the Al–8 wt%Ni alloy solidified from 750 °C (melting state) at a cooling rate of 18 K/min without and with a magnetic field, respectively. In the case of no field, it can be observed that the structure of the alloy has a usual disordered nature; however, after the application of a 10 T magnetic field, the Al_3Ni phase is aligned in such a way that the plane of the Al_3Ni phase is perpendicular to the magnetic field direction. Moreover, the microstructures of the Al–10 wt%Ni alloy solidified from 750 °C (melting state) without and with a magnetic field of 10 T have been investigated and the results are shown in Fig. 4. It can be learned that similar phenomena (plane-like structure) as the one in the Al–8 wt%Ni alloy has occurred and the primary Al_3Ni phase aligns with the Al_3Ni phase plane perpendicular to the magnetic field direction. However, compared with the phase alignment in the Al-8 wt%Ni, it can be found that the alignment of the Al_3Ni phase in the Al–8 wt%Ni is more regular than that in the Al–10 wt%Ni alloy. This means that the Ni content in the alloy has played an important role during the alignment of the Al_3Ni phase.

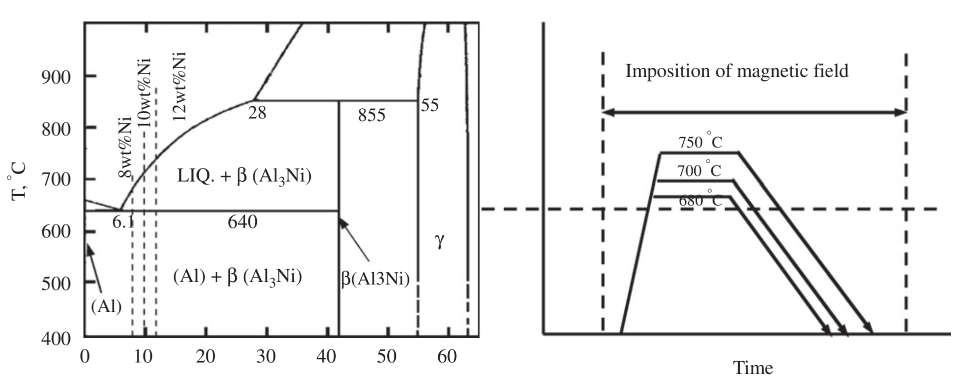

Fig. 2. Phase diagram of the Al–Ni alloy near Al (a); and temperature profiles for the solidification procedure (b).

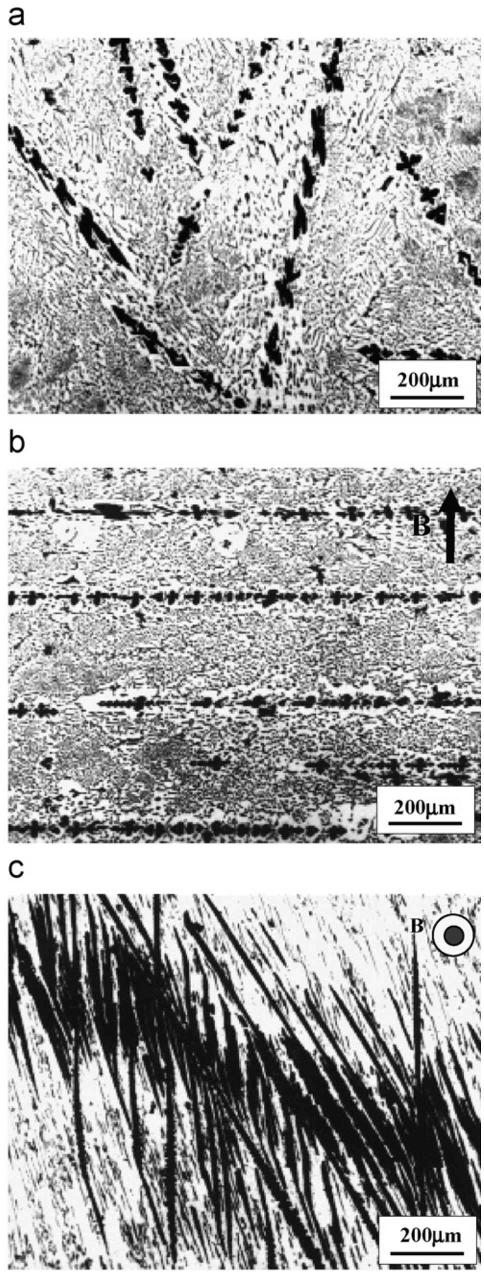

Fig. 3. Microstructures of the Al–8 wt%Ni alloy solidified from 750 °C at a cooling rate of 18 K/min: (a) 0 T; (b) 10 T, longitudinal microstructure; (c) 10 T, transverse microstructure.

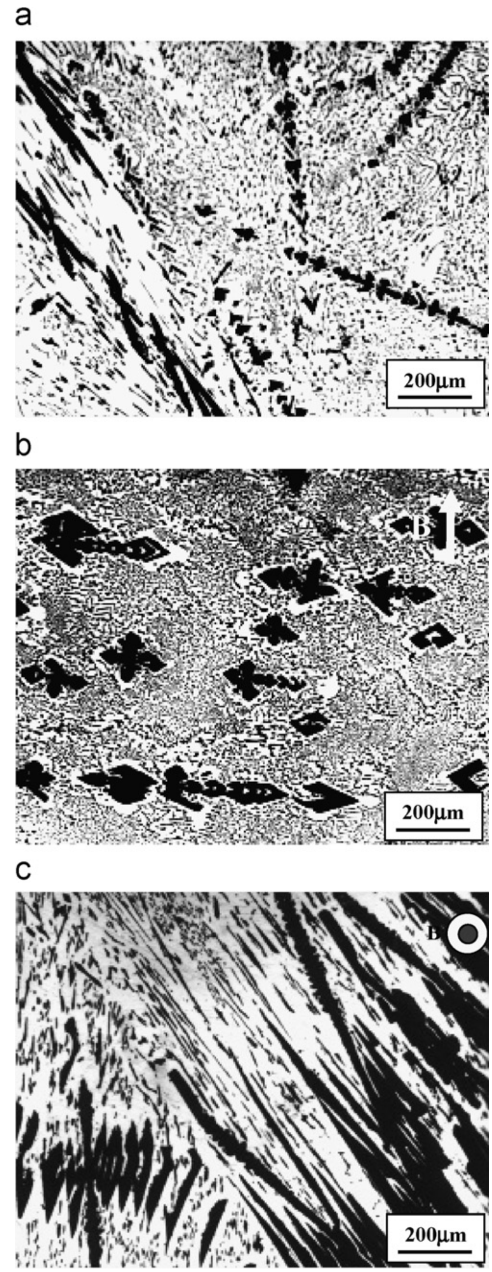

Fig. 4. Microstructures of the Al–10 wt%Ni alloy solidified from 750 °C at a cooling rate of 18 K/min: (a) 0 T; (b) 10 T, longitudinal microstructure; (c) 10 T, transverse microstructure.

Further, the alignment behavior of the Al_3Ni phase solidified from the semi-melting state has been investigated. Fig. 5 shows the microstructure of the Al-8 wt%Ni alloy solidified from 700 °C at a cooling rate of 18 K/min. It can be observed that the alignment of the Al_3Ni phase has occurred; however, compared with the one solidified from the melting state (Fig. 3(b) and (c)), the alignment is not so regular as that solidified from the melting state. This means that the primary Al_3Ni phase solidified from the melting state is easier to align.

Moreover, the effect of a magnetic field on the alignment of the Al_3Ni phase during the slow solidification process has been investigated and Fig. 6 shows the microstructures of the Al-8 wt%Ni alloy solidified from 750 °C (melting state) at a cooling rate of 1 K/min under a 10 T magnetic field. Fig. 6(a) and (b) shows the microstructures on the longitudinal and transverse sections, respectively. It can be observed that the regular crystal morphology has appeared on the longitudinal and transverse sections and the morphology on the longitudinal and transverse sections is different. This means that the alignment has also taken place during the slow solidification.

The effects of the magnetic field intensity and the solidification temperature on the alignment behavior of the Al_3Ni phase have been investigated in detail. Fig. 7 shows the microstructure solidified from 750 °C under various magnetic field intensities. It can be seen that with the increase of the magnetic field intensity the alignment of the Al_3Ni phase become regular. Under a magnetic field of 2 T, the regular aligned structure forms. Fig. 8 shows the microstructures solidified from various temperatures at a cooling rate of 18 K/min under a magnetic field of 10 T. It can be observed that with the increase of the solidification temperature

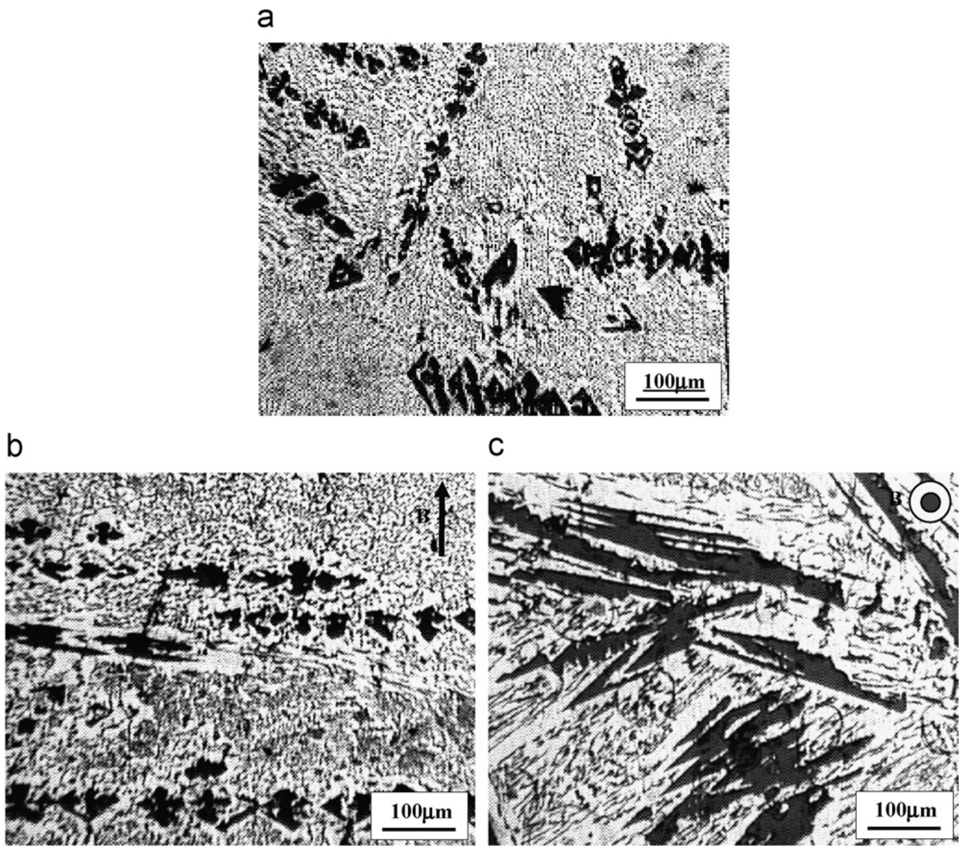

Fig. 5. Microstructures of the Al–8 wt%Ni alloy solidified from 700 °C at a cooling rate of 18 K/min: (a) 0 T; (b) 10 T, longitudinal microstructure; (c) 10 T, transverse microstructure.

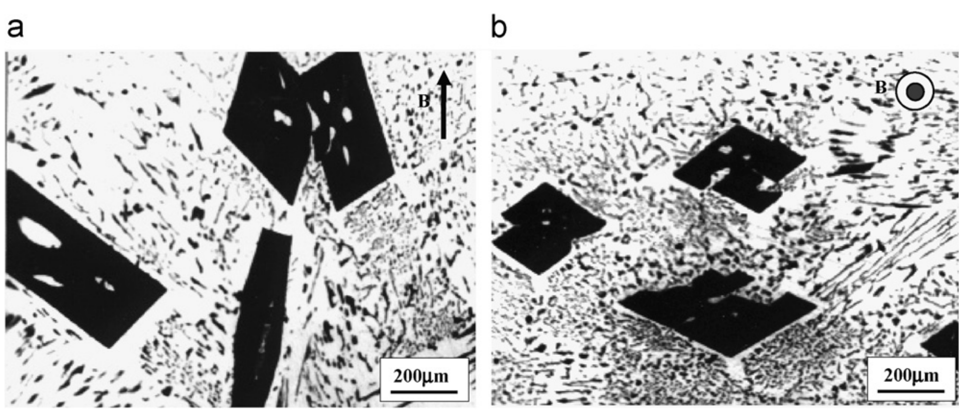

Fig. 6. Microstructures of the Al–8 wt%Ni alloy solidified from 750 °C at a cooling rate of 1 K/min under a 10 T magnetic field: (a) longitudinal section; (b) transverse section.

the alignment becomes regular, and when solidified at 680 °C the regular aligned structure has formed.

In order to quantify the alignment behavior of the Al_3Ni phase under various conditions, an alignment degree is defined as $\Gamma = N_0/N$, where N is the total number of crystals per unit of section area, and N_0 the number of orientation crystals. The Al_3Ni crystal is defined as the orientation crystal if the angle between its longer axis and the magnetic field is larger than 75°. Fig. 9 shows the dependences of the alignment degree Γ on the solidification temperature under a high magnetic field of 10 T for the Al–8 wt%Ni and Al–10 wt%Ni alloys, respectively. It can be learned that when the solidification temperature is below 650 °C the alignment degree is small. However, when the temperature exceeds 680 °C the alignment degree increases rapidly. Fig. 10 shows the dependence of the alignment degree Γ on the magnetic field for Al–8 wt%Ni, Al–10 wt%Ni and Al–12 wt%Ni alloys during solidified from 750 °C, respectively. It can be observed that when the magnetic field intensity exceeds a certain value the alignment degree Γ increases suddenly. It can also be learned that with the increase in the content of the Ni in the alloy, the alignment degree decreases. From Figs. 9 and 10, it can be learned that there exists a critical alignment temperature for the alloy solidified under a certain magnetic field. Fig. 11 shows the critical temperature for the Al–8 wt%Ni, Al–10 wt%Ni and Al–12 wt%Ni alloys under various magnetic fields, respectively. It can be observed that with the increase of the magnetic field intensity and the decrease of the Ni content in the alloy, the critical alignment temperature decreases.

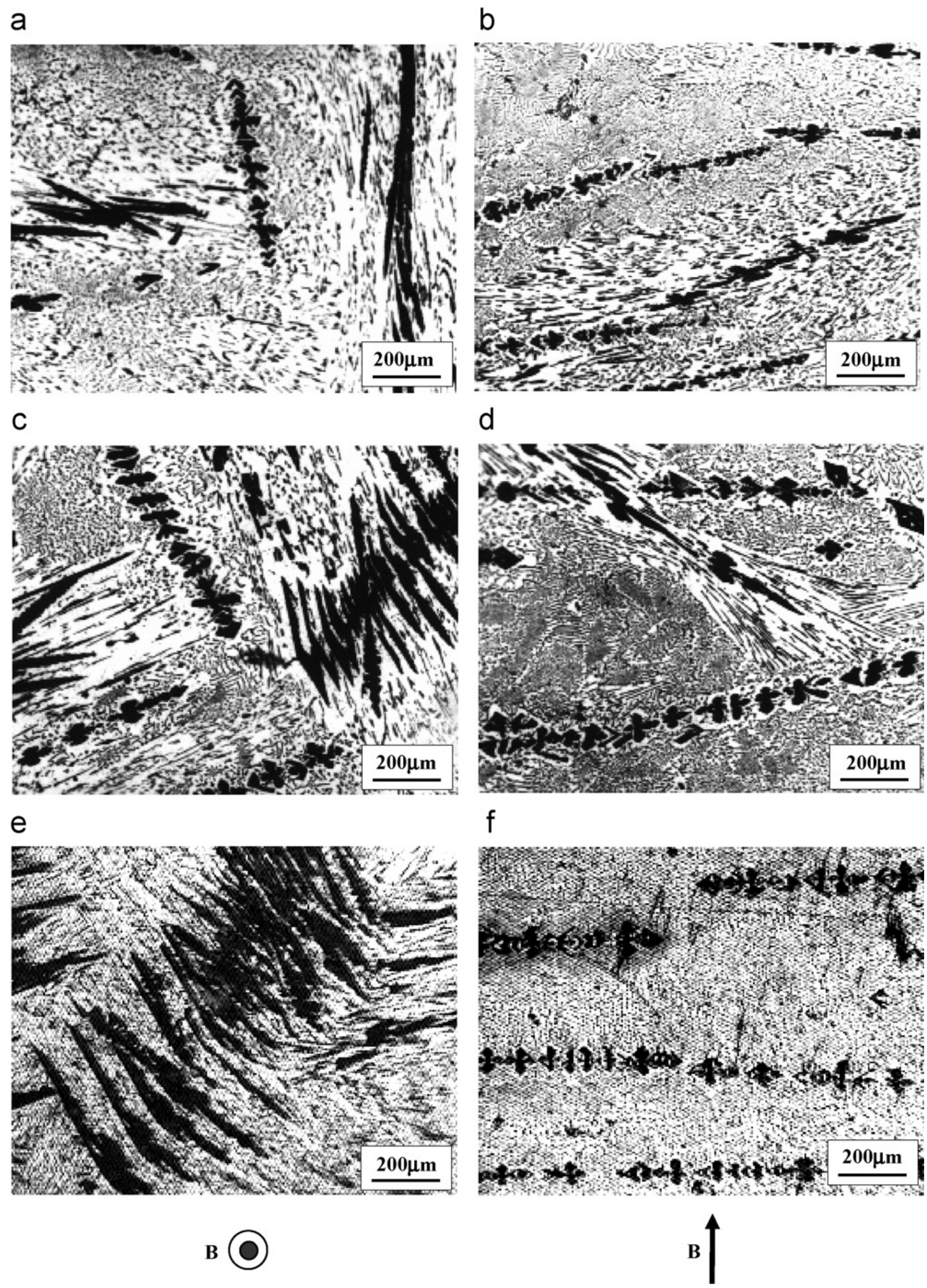

Fig. 7. Microstructure of the Al–8 wt%Ni alloy solidified from 750 °C at a cooling rate of 18 K/min under various magnetic field intensities: (a), (b) 1 T; (c), (d) 1.5 T; (e), (f) 2 T.

XRD and EBSD were applied to investigate the Al_3Ni crystal orientation. Fig. 12 shows the XRD for the sample of the Al–8 wt%Ni alloy solidified from 750 °C. It can be learned that the peak which indicates the (0 0 4) crystal plane on the section perpendicular to the magnetic field direction increases, and on the section parallel to the magnetic field direction the peaks which indicate the $(h\,k\,0)$-crystal planes increase by an application of the field. This means that the $\langle 0\,0\,1 \rangle$ crystal direction orients along the magnetic field direction. Fig. 13 shows the EBSD point analysis for the sample of the Al–8 wt%Ni alloy solidified from 750 °C. From the pole figure and inverse pole figure, it can be learned that the $\langle 0\,0\,1 \rangle$ crystal direction orients along the magnetic field direction and the $\langle 1\,0\,0 \rangle$, $\langle 1\,1\,0 \rangle$ and $\langle 0\,1\,0 \rangle$ crystal directions align perpendicular to the magnetic field. This shows that, along with the phase alignment, crystal orientation has occurred for the Al_3Ni crystal.

4. Discussion

From the above experimental results, it can be learned that the magnetic field has aligned the Al_3Ni phase and the effect of the magnetic field on the morphology of the Al_3Ni phase is weak. Moreover, it is found that the $\langle 0\,0\,1 \rangle$ crystal direction orients along the magnetic field direction. Therefore, the alignment of the Al_3Ni phase should be because to the rotating alignment caused the magnetocrystalline anisotropy of the Al_3Ni crystal. The orienting effect of the homogenous magnetic field on an

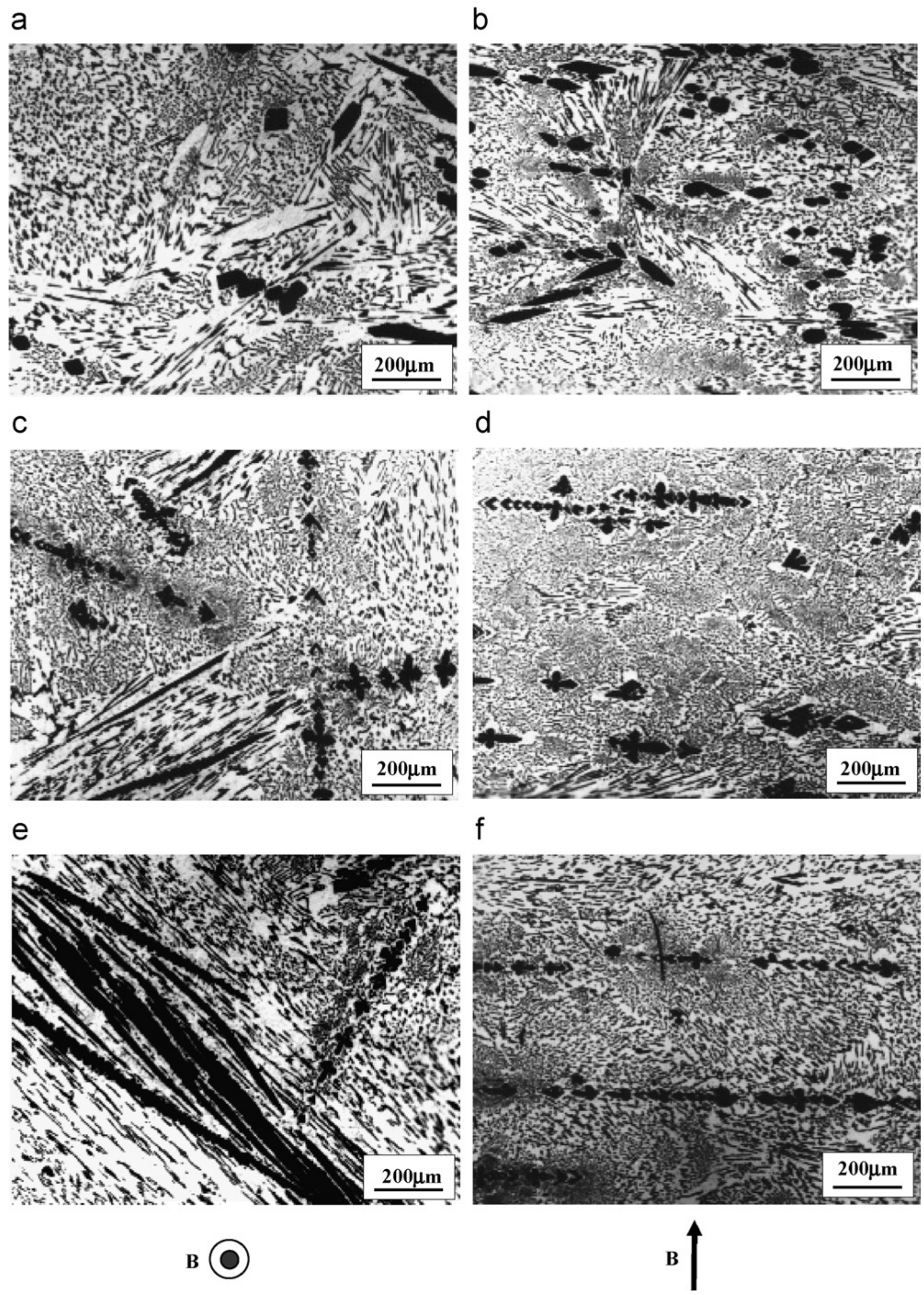

Fig. 8. Microstructure of the Al–8 wt%Ni alloy solidified from various temperatures at a cooling rate of 18 K/min under a magnetic field of 10 T: (a), (b) 670 °C; (c), (d) 675 °C; (e), (f) 680 °C.

anisotropic crystal characterized by an anomaly of magnetic susceptibility $\Delta\chi$ along two mutually perpendicular axes, without taking into consideration the influence of the crystal shape, can be deduced from the equation. [14]

$$T = \frac{\Delta\chi}{2\mu_0} B^2 V \sin 2\alpha, \quad (1)$$

where α is the angle between B and the axis with the maximum $|\chi|$. From the above equation, it follows that a paramagnetic crystal in the homogenous magnetic field will align itself with the easy magnetization axis along the magnetic field direction, while the diamagnetic crystal will position itself with the easy magnetization axis perpendicular to the magnetic field. It has been proved that the Al_3Ni phase is paramagnetic [15]. From the XRD and EBSD results, it can be learned that the *c*-axis (i.e., the $\langle 0\,0\,1 \rangle$ crystal direction) is its easy magnetic axis. Moreover, Al_3Ni crystal is orthorhombic and possesses distinct growth anisotropy, and the $\langle 0\,1\,0 \rangle$ crystal direction is the preferred growth direction [16]. Fig. 14(a) and (b) shows schematic drawings of crystal structure and the dendrite morphology, respectively. Thus, along with the rotation of the $\langle 0\,0\,1 \rangle$ crystal direction along the magnetic field, the longer axis of the dendrite (the $\langle 0\,1\,0 \rangle$ crystal direction) is perpendicular to the magnetic field. As a consequence, the plane of the Al_3Ni phase will form as shown in Fig. 14(c) and (d). In principle, the orienting action of the magnetic field must always affect a crystal with magnetic anisotropy; however, owing to the

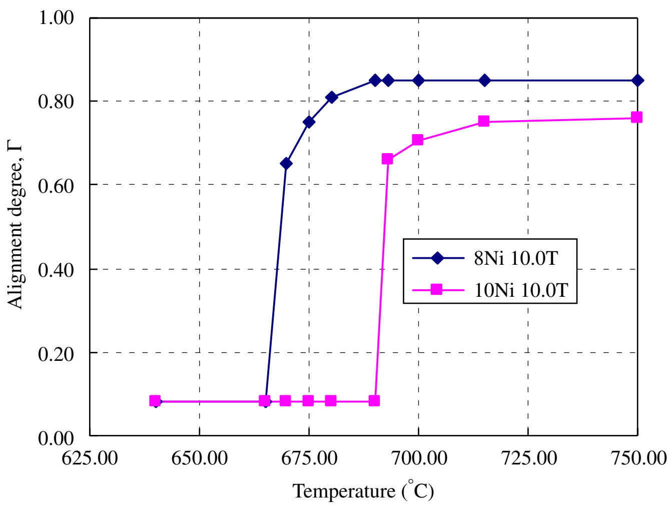

Fig. 9. Dependences of the alignment degree Γ of the primary Al3Ni phase on the solidification temperature under a high magnetic field of 10 T for the Al–8 wt% and Al–10 wt% alloys, respectively.

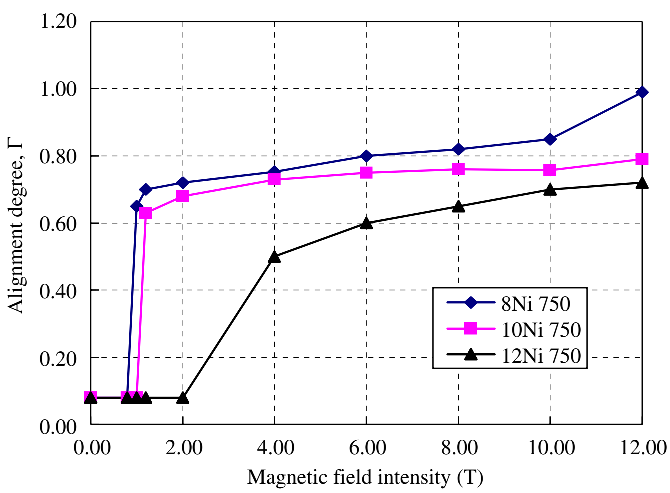

Fig. 10. Dependences of the alignment degree Γ of the primary Al_3Ni phase on the magnetic field for the Al–8 wt%Ni, Al–10 wt%Ni and Al–12 wt%Ni alloys during the solidification from 750 °C, respectively.

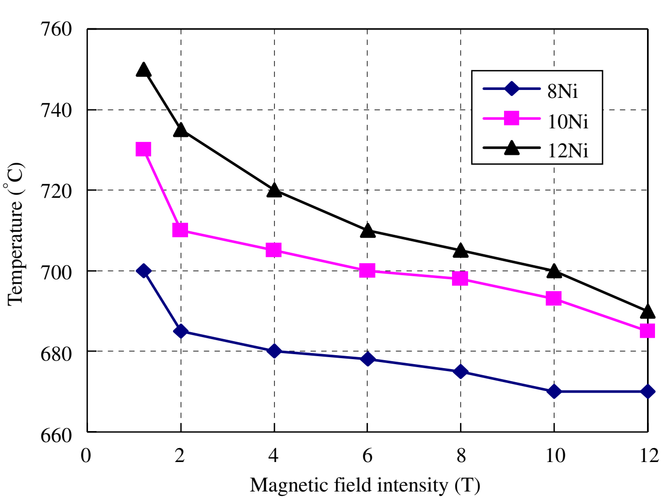

Fig. 11. The critical alignment temperature of the primary phase Al_3Ni vs. magnetic intensity for the Al–8 wt%Ni, Al–10 wt%Ni and Al–12 wt%Ni alloys, respectively.

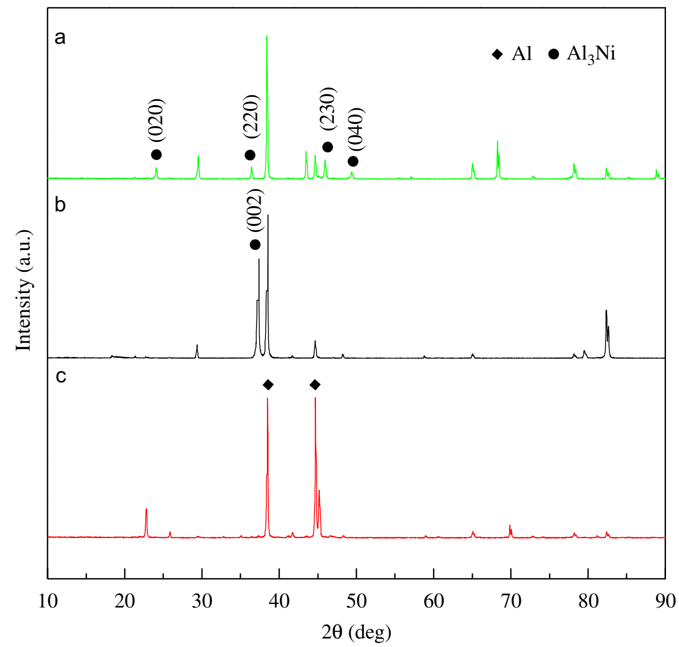

Fig. 12. XRD of the samples in Fig. 3: (a) longitudinal section; (b) transverse section; (c) without magnetic field.

existence of viscous forces, convective flows in the melt and the interaction of the crystals with each other and the walls of the crucible, the alignment may not occur. First of all, when a dendrite rotates, the liquid viscosity induces a rotating torque R that prevents its rotation:

$$R \sim r^3 \eta v \tag{2}$$

where η is the viscosity and v is rotating speed. Moreover, when an electrically conductive substance rotates in a magnetic field, a current induced due to the interaction of rotational motion and a magnetic field will be produced, as a consequence, Lorenz force as an electromagnetic force is induced by the interaction of the current and the given magnetic field . The force that acts on the particle to suppress its rotation is given by

$$F \sim \sigma B^2 r v \tag{3}$$

where σ is conductance coefficient.

From the above analysis, it is easy to learn that with the increase of the magnetic field intensity the magnetic torque T increases; as a consequence, the alignment factor increases. It can also be learned that the smaller the grain , the smaller the rotating torques induced by the liquid viscosity and Lorenz force . This means that the smaller the grain, the easier the alignment of the primary phase. However, the magnetic orientation works only when the magnetization energy is larger than a thermal energy kT [17]. This condition can be described as follows:

$$V \frac{\Delta\chi}{2\mu_0} B^2 > kT \tag{4}$$

where k is Boltzmann constant. Therefore, the particle radius should be larger than a certain value, and then the orientation will occur. This means that the phase has an optimal size for the alignment under a certain condition. When the primary Al_3Ni phase is solidified from the melting state under a high magnetic field the nucleus crystallizing from the melt will grow up, and when the size of the phase increases to the optimal size the regular alignment structure will form. However, when the alloy is solidified from the semi-melting state, as the size of some primary

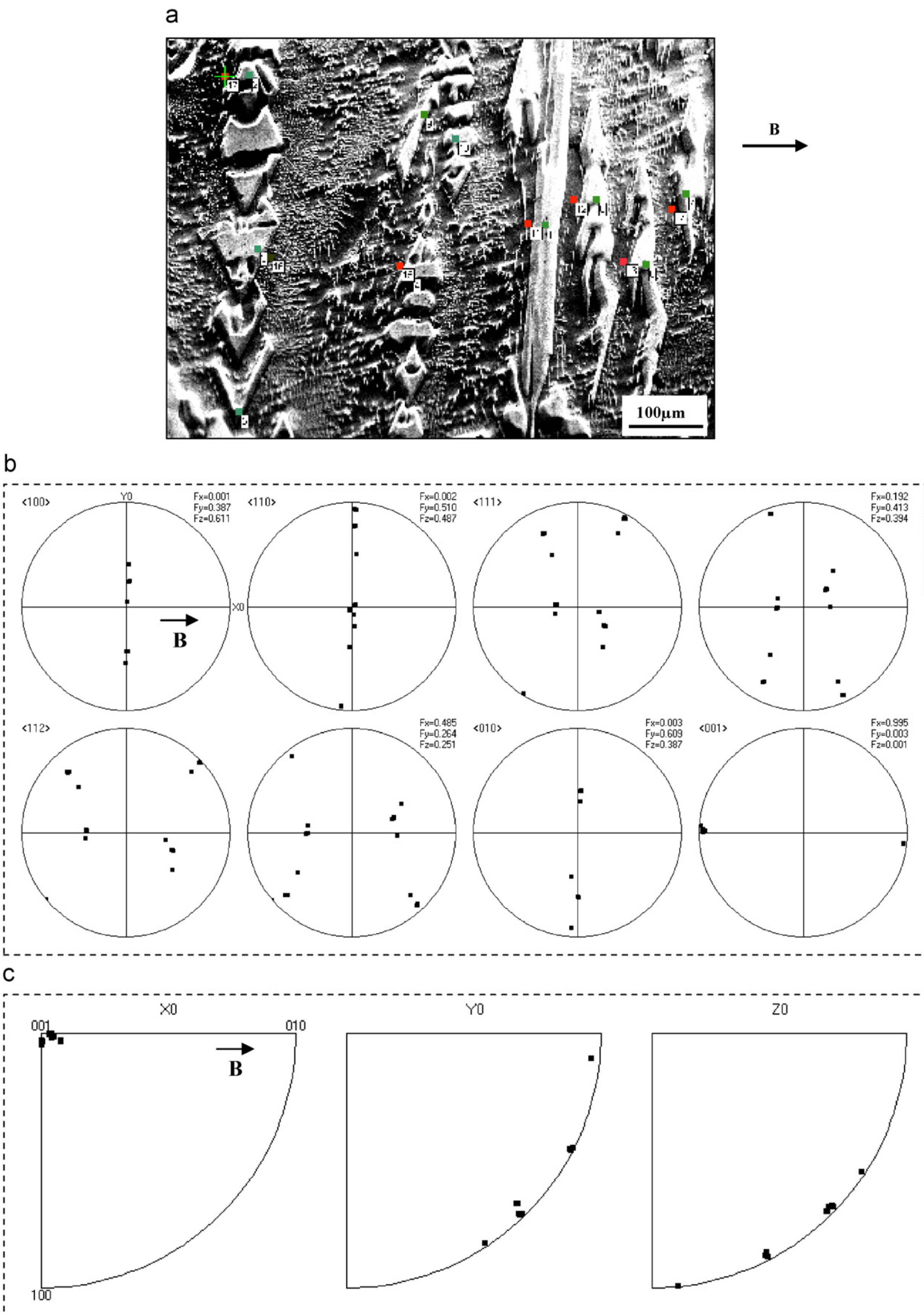

Fig. 13. (a) EBSD point analysis for the alignment of the Al_3Ni phase on the longitudinal section solidified the Al–8 wt%Ni alloy from 750 °C at a cooling rate of 18 K/min; (b) pole figure; (c) inverse pole figure.

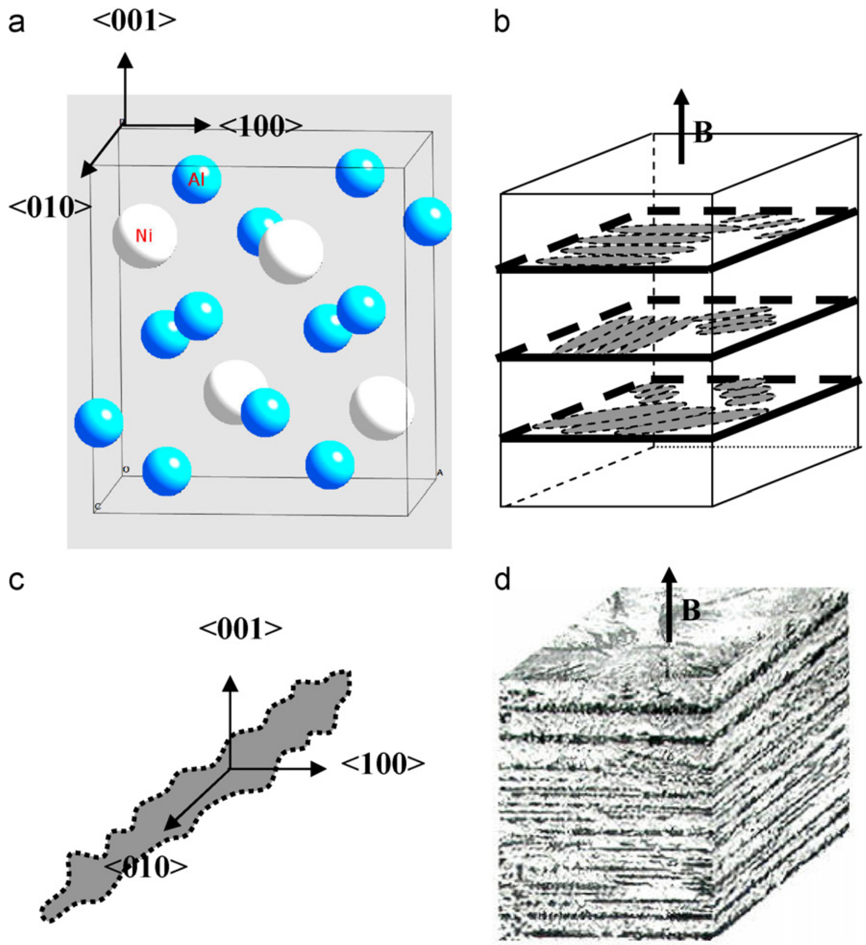

Fig. 14. Al_3Ni crystal structure and the alignment of the dendrite under a magnetic field: (a) Al_3Ni crystal structure; (b) dendrite morphology along various directions; (c) schematic of the dendrite alignment under a magnetic field; (d) the three-dimensional diagram of the Al–8 wt%Ni sample solidified from 750 °C at a cooling rate of 18 K/min.

phases is larger than the optimal size, these phases could not get the regular alignment. Moreover, the viscous forces will increase with the decrease of temperature; therefore, when the alloy is solidified from the semi-melting state, normally it is not easy to get a regular alignment. The above results show that with the increase of the Ni composition the alignment degree decreases. This should be attributed to the increase of the viscous forces with the increase of the alloy composition. Moreover, owing to the increase of the composition, the phase crystallizing speed will increase; thus, the interaction between the phases will increase. This will block the formation of the regular aligned structure.

5. Conclusion

Influences of a high magnetic field on the alignment behavior of the primary Al_3Ni phase in the Al–Ni alloys have been investigated. It has been found that the plane alignment of the Al_3Ni phase perpendicular to the magnetic field has occurred. By means of the XRD and EBSD analysis, it is found that the $\langle 001 \rangle$ crystal direction of the Al_3Ni crystal orients along the magnetic field and the $\langle 100 \rangle$, $\langle 110 \rangle$ and $\langle 010 \rangle$ crystal directions orient perpendicular to the magnetic field. Moreover, the alignment influencing factors have been investigated and it is found that the magnetic intensity, solidification temperature and alloy composition play great roles during the aligning process. Indeed, it is observed that, under a certain magnetic field intensity, when the solidification temperature exceeds the critical value the alignment degree increases with the increase of the solidification temperature, and that, under a certain solidification temperature, when the magnetic field intensity exceeds the critical value the alignment degree increases with the increase of the magnetic field intensity. With the increase of the Ni content, the critical alignment values of the magnetic field intensity and the solidification temperature increase. The above results are discussed based on the magnetocrystalline anisotropy of the Al_3Ni crystal and the rotating alignment of the primary phase under a high magnetic field.

Acknowledgments

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