FeSiBPCu Nanocrystalline Soft Magnetic Alloys with High Bs of 1.9 Tesla Produced by Crystallizing Hetero-Amorphous Phase

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FeSiBPCu Nanocrystalline Soft Magnetic Alloys with High $B_s$ of 1.9 Tesla Produced by Crystallizing Hetero-Amorphous Phase

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Technically important nanocrystalline soft magnetic alloys and their derivatives always include metal elements such as Nb, Zr, Mo, etc. and/or Cu to realize the nanostructure, which results in a remarkable decrease of saturation magnetic flux density ($B_s$) and a significant increase in material cost. With the aim to solve the serious problem, we successfully developed new FeSiBPCu nanocrystalline soft magnetic alloys. The melt-spun Fe$_{83.3}$Si$_{3.8}$B$_3$P$_3$Cu$_{0.7}$ (at%) alloys have heterogeneous amorphous structures including a large amount of $\alpha$-Fe clusters, 2–3 nm in size, due to the unusual effect of the simultaneous addition of the proper amounts of P and Cu. The hetero-amorphous alloys exhibit higher $B_s$ of about 1.67 T than the representative amorphous and the nanocrystalline alloys, and the low coercivity ($H_c$) of 5–10 Am$^{-1}$. A homogeneous nanocrystalline structure composed of small $\alpha$-Fe grains with a size of about 10 nm can be realized by crystallizing the hetero-amorphous alloys. The nanocrystalline alloys show extremely high $B_s$ of 1.88–1.94 T almost comparable to the commercial Fe-3.5 mass%Si crystalline soft magnetic alloys, and low $H_c$ of 7–10 Am$^{-1}$ due to the simultaneous realization of the homogeneous nanocrystalline structure and small magnetostriction of 2–3 × 10$^{-6}$. In addition, the alloys have a large economical advantage of lower material cost and better productivity than the ordinary soft magnetic nanocrystalline alloys now in practical use.

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Keywords: soft magnetic material, high saturation magnetic flux density, amorphous alloy, nanocrystalline alloy

1. Introductions

Nanocrystalline soft magnetic alloys$^{1-3}$ produced by crystallizing amorphous phases attracted great attention due to their excellent soft magnetic properties and rather high magnetizations. The developed nanocrystalline soft magnetic alloys and their derivatives always include a large amount of metal elements such as Nb, Zr, Mo, etc. and/or Cu to realize the nanocrystallized structure.$^{4-8}$ It is well-known that the uniform nanocrystalline structure with excellent magnetic softness can be obtained by an amorphous precursor including some chemical or topological heterogeneities induced by the above-mentioned metal elements.$^{9,10}$ During heating, an apparent short-medium range ordering$^{11}$ or a nanoscale phase separation$^{12}$ in the amorphous matrix raises from the heterogeneity, which acts as the nucleation site for the primary crystal and leads to the refinement of the grains. Thus, the precursor for nanocrystallized structure is needed to be an amorphous phase essentially including the metal elements, however, which cause a remarkable decrease of the saturation magnetic flux density ($B_s$)$^{13}$ and a significant increase of the material cost. Considering current energy problems, higher $B_s$ accompanied with excellent magnetic softness is strongly required for the magnetic materials used in electrical power supplies.

We developed new Fe$_{83.3}$Si$_{3.8}$B$_3$P$_3$Cu$_{0.7}$ (at%) nanocrystalline soft magnetic alloys with much higher $B_s$ of around 1.9 T than those of the representative amorphous, the ordinary$^{1-3,5,8}$ and the recently reported$^{14,15}$ nanocrystalline alloys, almost comparable to Fe-3.5 mass%Si crystalline alloys$^{16}$ now in practical use.

2. Experimental Procedure

FeSiBPCu alloy ingots were produced by induction-melting mixtures of Fe (99.98 mass%), Si (99.998 mass%), B (99.5 mass%), Cu (99.99 mass%) and premelted Fe-P (99.9 mass%) in a high purity Argon atmosphere. Fe$_{78}$Si$_3$B$_{13}$ alloy ingot was also prepared by the same method for comparison. A single-roller melt-spinning method in air was used to produce the rapidly solidified tapes with about 1–3 mm in width and approximately 20 μm in thickness. The alloy compositions are nominally expressed since the difference between nominal and chemical analyzed composition was negligibly small. The structure was identified by X-ray diffractometry (XRD) and transmission electron microscopy (TEM). The mean grain size of the $\alpha$-Fe phase was estimated by using Scherrer’s equation from the full width at half maximum of the bcc(110) reflection peak from for the specimens. Thermal property of melt-spun alloys was evaluated with a differential scanning calorimeter (DSC) at a heating rate of 0.67°C/s under an Argon flow. The melt-spun specimens were subjected to annealing for 600 seconds at various temperatures in a vacuum atmosphere under the non-magnetic field. Saturation magnetization ($J_s$) and coercivity ($H_c$) under a maximum applied field of 800 kAm$^{-1}$ and 2 kAm$^{-1}$ were measured by a vibrating sample magnetometer (VSM) and a dc $B$-$H$ loop tracer, respectively. Effective permeability ($\mu_e$) at 1 kHz and core loss ($W$) at 50 Hz for were measured with a vector impedance analyzer under a field of 0.4 Am$^{-1}$ and an ac $B$-$H$ analyzer operated under sinusoidal input voltage, respectively, by using the wounded toroidal cores with a diameter of about 20 mm. The $W$ and $\mu_e$ should be inferior to those measured by using a single sheet and a ring sample. Magnetostriction was measured in an applied field up to 800 kAm$^{-1}$ by using a strain gauge. Density was measured by the Archimedean method with n-tridecane.

3. Results and Discussion

3.1 Microstructure of as-quenched alloys

Figure 1 shows the dependence of $\alpha$-Fe grain size on the substitutional amounts of P for B and Cu for Fe in an as-
quenched Fe₂SiB₉ alloy with higher Fe content than the limit of about 80% for the formation of a single amorphous structure. The grain size is estimated from a sharp diffraction peak at about 45° corresponding to α-Fe phase in the XRD profiles or the high resolution TEM (HRTEM) images. The alloy without P and Cu has the largest α-Fe grains with the size of 93 nm estimated from XRD profile, shown in Fig. 2(a). The grain size decreases with the P and/or Cu addition, and reaches to the minimum values of around 3 nm smaller for the alloys simultaneously containing 2–4 at%P and 0.3%Cu. The grain size for the alloys with the proper amounts of P and Cu is much smaller than that for the recently reported the FeCuB(Si) alloys. The XRD profile, the HRTEM image and the selected area electron diffraction (SAED) pattern of the as-quenched Fe₈₁.₇Si₉B₇P₂Cu₀.₃ alloy are shown in Fig. 2(b), Fig. 3(a) and (b), respectively. The SAED pattern shows diffused diffraction rings and no spots corresponding to any crystalline phase in agreement with the XRD results shown in Fig. 2(b). However, the HRTEM image reveals that the as-quenched structure of the alloy is not fully amorphous in disagreement with the XRD and the SAED patterns, but consists of an extremely small crystalline-like phase with about 3 nm or smaller in diameter, randomly dispersed within the amorphous matrix. Judging from the lattice fringes as indicated by white bars in Fig. 3(a), corresponding to the bcc (110) plane distance of α-Fe crystalline, the phase is completely revealed to be α-Fe crystal. It is understandable that the XRD and the SAED patterns are not able to reveal the existence of the nano-crystals due to their very small size and low volume fraction. Therefore, we can notice that the coarse α-Fe grains formed within the as-quenched amorphous matrix of Fe₈₂Si₂B₉ alloy change to the nano-sized α-Fe phase with 3 nm or smaller in size by the simultaneous substitution of 2–4%P for B and 0.3%Cu for Fe. With deviation from these compositions with the P and the Cu contents, the grain size rapidly increases.

We discuss on the origin of the remarkable effect of the simultaneous addition of P and Cu on the refinement of the α-Fe crystals formed in the amorphous matrix of the alloys with

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Fig. 1 Dependance of α-Fe grain size on substitutional amounts of P for B and Cu for Fe in Fe₈₂₋ₓSi₉B₉₋ₓPₓCuₓ in an as-quenched state.

Fig. 2 XRD profiles for as-quenched (a) Fe₈₂Si₂B₉ and (b) Fe₈₁.₇Si₉B₇P₂Cu₀.₃ alloys.

Fig. 3 (a) HRTEM image and (b) SAED pattern for as-quenched Fe₈₁.₇Si₉B₇P₂Cu₀.₃ alloy.
higher Fe content than the limit for formation of a single amorphous phase. Taking account of the result that the effect is observed only for the simultaneous addition of the proper amounts of P and Cu, the mixing enthalpy ($\Delta H$) between the constituent elements is considered. It is noted that $\Delta H$ is positive (+13 kJ/mol) between Fe and Cu and negative (−9 kJ/mol) between Cu and P, suggesting that there is a repulsive and an attractive interactions existing between Fe and Cu, and Cu and P atoms, respectively. Therefore, during melt-spinning, an extremely small region including enriched Cu and P elements could separate from the Fe-Si-B-(P) amorphous phase and possibly act as the nucleation sites for $\alpha$-Fe clusters, which should result in the refinement of the grains. The number and the size of the Cu- and P-rich region possibly change with the amounts of P and Cu. The simultaneous addition of 2–4%P and around 0.3%Cu might realize the smallest size and the largest number of the region, which is considered to be most suitable condition for decreasing the $\alpha$-Fe precipitates.

Figure 4 shows the compositional dependence of $H_c$ on P and Cu contents for as-quenched Fe$_{82-x}$Si$_9$B$_9$P$_x$Cu$_y$ ($x$: 0–6, $y$: 0–0.4) alloys. The dependence coincides with the change in the $\alpha$-Fe grain size with P and Cu addition shown in Fig. 1. The alloy without the addition of P and Cu has the largest $H_c$ of about 45 Am$^{-1}$ responsible to the coarse $\alpha$-Fe grains. The $H_c$ decreases with decreasing the grain size, and reaches the minimum value of 7–8 Am$^{-1}$ for the hetero-amorphous alloys with 2–4%P and around 0.3%Cu.

The similar effect of the simultaneous addition of P and Cu was observed for the alloys with higher Fe content up to 85.7%. Figure 5 shows the XRD profiles for Fe$_{83.3}$Si$_4$B$_8$P$_4$Cu$_0.7$ (“A” alloy), Fe$_{84.3}$Si$_4$B$_8$P$_3$Cu$_0.7$ (“B” alloy) and Fe$_{85.7}$Si$_4$B$_9$P$_1$Cu$_0.3$ (“C” alloy), indicating an amorphous structure with small $H_c$ of 7, 8 and 11 Am$^{-1}$, respectively. Whereas, the HRTEM observation revealed that the alloys have an as-quenched hetero-amorphous structure with a large amount of $\alpha$-Fe clusters, as shown in Fig. 6 for “A” alloy as an example. The hetero-amorphous alloys have higher $B_c$ of about 1.67 T than the FeSiB amorphous alloy now in practical use. Moreover, all the alloys shown in Fig. 1 and hetero-amorphous “A”, “B” and “C” alloys are confirmed to be completely ductile in three-point bending test, which is important for applications.

### 3.2 Microstructure and magnetic properties of crystallized alloys from hetero-amorphous phase

Crystallization behavior was examined by DSC for the hetero-amorphous “A” and “B” alloys, shown in Fig. 7. The alloys crystallize through two exothermic peaks and large temperature intervals of 168°C and 135°C between each one, respectively. It was confirmed by XRD that the first and the second peaks on the curves result from the phase transition from the amorphous to $\alpha$-Fe and then to some compounds, respectively. It has already been reported in the representative nanocrystalline soft magnetic alloys “Nanoperm” that the amorphous precursor with a large temperature
interval can change to a uniform nanocrystalline structure without any compounds with large magnetocrystalline anisotropy by annealing within the temperature range between the two peaks.

Figure 8 shows the XRD profiles for “A” and “B” alloys crystallized at 475°C and 450°C, respectively, between the temperatures of the two peaks on the DSC curves. The structures were found to consist of α-Fe phase, whose grain sizes were estimated to be 11 nm and 17 nm for “A” and “B” alloys, respectively. The SAED profile and the TEM image of nanocrystalline “A” alloy are shown in Fig. 9. A uniform nanocrystalline structure with the grain size of approximately 10 nm, which is in almost agreement with the estimated value from the XRD profile, is successfully formed presumably because the cluster formed at an as-quenched state could act as the nucleation site for the α-Fe grains during the crystallization. The structure is very similar to the previously developed representative nanocrystallized alloys with excellent magnetic softness in spite of not-containing a large amount of the metal elements.

Figure 10 shows the hysteresis loop the nanocrystalline “A” alloy. The alloy shows the extremely high \( B_s \) of 1.88 T due to the high Fe content and almost not-containing any metal elements except for Fe. The \( B_s \) is higher than those of the amorphous and the previously reported nanocrystalline alloys, and slightly lower than the Fe-3.5 mass%Si crystalline soft magnetic alloys. “A” alloy also exhibits the low \( H_c \) of 7 Am\(^{-1}\) and the high \( \mu_e \) of 25,000 due to the simultaneous realization of the homogeneous nanocrystalline structure and the much smaller magnetostriction \( (\lambda) \) of \( +2 \times 10^{-6} \) than that of \( +27 \times 10^{-6} \) of Fe\(_{78}\)Si\(_6\)B\(_{13}\) amorphous alloy.
The nanocrystalline alloys should make a contribution to energy saving though their low core losses and improve the conversation of earth resources. In addition, the alloys have a large economical advantage of low material cost and good productivity because of not-containing expensive and easily oxidized metal elements which has been considered to be essential for the nanocrystalline soft magnetic alloys.

4. Conclusions

Structure and magnetic properties of as-quenched and crystallized Fe-rich FeSiBPCu alloys were studied. The uniform nanocrystalline structure composed of α-Fe grains is found to be realized by annealing the hetero-amorphous structure with α-Fe clusters formed by an unusual effect of the simultaneous addition of P and Cu. The conclusions obtained are summarized as follows.

(1) The simultaneous substitution of 2–4%P for B and 0.3%Cu for Fe significantly and drastically decreases the size of α-Fe grains within the as-quenched amorphous matrix of an as-quenched Fe₈₂Si₈B₄ alloy from 93 nm to 3 nm or smaller. That refinement effect was also observed for the alloys with higher Fe content up to 85.7%.

(2) The melt-spun Fe₈₃.₃₋₈₄.₃Si₄B₄P₃₋₄Cu₀₋₇ alloys with heterogeneous amorphous structures including a large number of α-Fe clusters exhibit higher Bₘ of about 1.67 T than the representative Fe₇₃Si₈B₁₃ amorphous alloy, and the low Hₘ of 5–10 Am⁻¹.

(3) The uniform nanocrystallized structures from the hetero-amorphous alloys consist of small α-Fe grains with about 10 nm evaluated from the TEM image and 17 nm estimated from the XRD profile in size for Fe₈₃.₃Si₈B₄P₃Cu₀₋₇ and Fe₈₄.₃Si₄B₄P₃Cu₀₋₇, respectively. With the structural change from the amorphous to the nanocrystalline structure, the Bₘ rapidly increases from 1.67 T to 1.88–1.94 T.

(4) The Bₘ of the nanocrystalline alloys is considerably higher than those of any soft magnetic amorphous and nanocrystalline alloys previously reported.

(5) The Fe₈₃.₃Si₈B₄P₃Cu₀₋₇ nanocrystalline alloy exhibits excellent magnetic softness, Hₘ of 7 Am⁻¹ and μₑ of 25,000 at 1 kHz, due to the simultaneous realization of the uniform nanostructure composed by small α-Fe grains with about 10 nm in size and a small magnetostriction of 2 × 10⁻⁶.

(6) The Fe₈₃.₃Si₈B₄P₃Cu₀₋₇ nanocrystalline alloy exhibits the extremely lower W over the whole Bₘ range than the Fe₇₃Si₈B₁₃ amorphous alloy. The rapid increase of W takes place at higher Bₘ of 1.7 T for the nanocrystalline alloy than that of 1.4 T for the amorphous alloy.

REFERENCES

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