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# Novel FePBNbCr glassy alloys "*SENNTIX*" with good soft-magnetic properties for high efficiency commercial inductor cores

Hiroyuki Matsumoto[a,*], Akiri Urata[a], Yasunobu Yamada[a], Akihisa Inoue[b]

[a] NEC Tokin Corporation, 6-7-1 Koriyama, Sendai, Miyagi 982-8510, Japan
[b] Tohoku University, 2-1-1 Katahira, Sendai, Miyagi980-8577, Japan, Hiroyuki Matsumoto

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ABSTRACT

According to a recent study, Fe-based glassy alloys are expected good soft-magnetic properties such as high saturation magnetization and lower coercive force. We focused on Fe-based glassy alloys and have succeeded in developing novel glassy $Fe_{97-x-y}P_xB_yNb_2Cr_1$ ($x$ = 5–13, $y$ = 7–15) alloys for an inductor material. The glassy alloy series of $Fe_{97-x-y}P_xB_yNb_2Cr_1$ ($x$ = 5–13, $y$ = 7–15) have high glass-forming ability with the large critical thickness of 110–150 μm and high $B_s$ of 1.25–1.35 T. The glassy alloy powder with chemical composition $Fe_{77}P_{10.5}B_{9.5}Nb_2Cr_1$ exhibits an excellent spherical particle shape related to the lower melting point and liquid phase point. In addition, Fe–P–B–Nb–Cr powder/resin composite core has much lower core loss of 653–881 kW/m$^3$, which is approximately 1/3 lower than the conventional amorphous Fe–Si–B–Cr powder/resin composite core and 1/4 lower than the conventional crystalline Fe–Si–Cr powder/resin composite core due to the lower coercive force of 2.5–3.1 A/m. Based on above results, the glassy $Fe_{77}P_{10.5}B_{9.5}Nb_2Cr_1$ alloy powder enable to achieve ultra-high efficient and high quality products in a commercial inductor. In fact, the surface mounted inductor using Fe–P–B–Nb–Cr powder/resin exhibits the high efficiency of approximately 2.0% compared with the conventional inductors made of the crystalline Fe–Si–Cr powder/resin composite core.



## 1. Introduction

According to the technical trend of small and high performance devices, "Note-PC, Mobile-Phones" and so on, the achievement of a high level of power efficiency is required in power supply circuits. The surface mount device type inductor in the power supply is expected to deal satisfactorily with high-current supply and to improve the power loss characteristic. In order to improve these characteristics of power supply, the soft magnetic material for inductor cores is required to have high $B_s$ and low core losses. However, the conventional Ni–Zn ferrite and Mn–Zn ferrite core cannot be used as core materials of inductors for large current power supplies because the $B_s$ of 0.5 T is much lower as compared with other soft magnetic materials consisting of metallic alloys. On the other hand, commercial soft magnetic materials consisting of metallic alloys, especially Fe-based materials, have the subject associated with high hysteresis loss that is attributed to large magnetic anisotropy. Hence, we focused on glassy metallic alloys with both high saturation magnetization and low magnetic anisotropy, and developed the Fe-based glassy metallic alloy with a composition of $Fe_{77}P_7B_{13}Nb_3$ for inductor core materials [1]. Corrosion resistance is also one of the important factors in practical use for commercial inductor core materials, as same as the soft magnetic properties. Thus, we tried to improve the corrosion resistance and succeeded in developing a novel glassy alloy with a chemical composition of $Fe_{77}P_7B_{13}Nb_2Cr_1$ for a new class material of inductor cores [2]. In this paper, we report on a novel glassy alloy $Fe_{97-x-y}P_xB_yNb_2Cr_1$ with high $B_s$ of 1.3 T, low $H_c$ of 2.0 A/m by the low crystalline anisotropy, a low core loss of 881 kW/m$^3$, a high corrosion resistance and excellent spherical particle shape in the produced powder. The surface mounted inductor using the glassy $Fe_{77}P_{10.5}B_{9.5}Nb_2Cr_1$ alloy powder/resin composite core exhibits a higher efficiency of about 2.0% compared with the conventional inductor made of crystalline $Fe_{85}Si_{9.5}Cr_{5.5}$ powder/resin composite core. In addition, high glass-forming ability (GFA) is obtained even in case of using the raw ferroalloy materials of low costs.

### 2. Experimental procedures

$Fe_{97-x-y}P_xB_yNb_2Cr_1$, $Fe_{77}P_xB_{20-x}Nb_2Cr_1$ and $Fe_{85}Si_{9.5}Cr_{5.5}$ were prepared by induction melting the mixture of pre-melted Fe–P, Fe–B, Fe–Nb, Fe–Cr, Fe–Si and pure Fe in an argon atmosphere. The alloy compositions represent the nominal atomic percents. Glassy $Fe_{97-x-y}P_xB_yNb_2Cr_1$, $Fe_{77}P_xB_{20-x}Nb_2Cr_1$ alloys and amorphous $Fe_{75}Si_{10}B_{12}Cr_3$ alloy were produced as ribbon form having a width of about 1 mm and thicknesses of 25–150 μm by a single roller melt-spinning method in an argon atmosphere. The melting point ($T_m$) and the liquid phase point ($T_l$) were measured by differential thermal analysis (DTA) at a heating rate of 0.17 K/s. The glass

* Corresponding author. Tel.: +81 22 308 0028; fax: +81 22 308 1132.
*E-mail address:* matsuhiro@nec-tokin.com (H. Matsumoto).

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transition temperature ($T_g$), crystallization temperature ($T_x$) and Curie temperature ($T_c$) were determined by differential scanning calorimetry (DSC) at a heating rate of 0.67 K/s. The saturation magnetic flux density ($B_s$) was measured under an applied field of 400 kA/m with a vibrating sample magnetometer (VSM). The coercive force ($H_c$) was measured under a field of 1 kA/m with a DC B-H loop tracer at room temperature and after annealing at 623 K. The glassy $Fe_{97-x-y}P_xB_yNb_2Cr_1$, amorphous $Fe_{75}Si_{10}B_{12}Cr_3$ and crystalline $Fe_{85}Si_{9.5}Cr_{5.5}$ alloy powders were produced by water atomization. The particle shape of these alloys is observed by scanning electron microscopy (SEM). Powders with an average particle size of 12 μm were mixed with a resin binder and produced in a ring core form of φ 13 mm × φ 8 mm × 6.5 mm and a surface mounted device (SMD) type choke coil of 10 mm × 10 mm × 4 mm with a packing density of 71–73% under a molding pressure of 8.0 GPa after granulation. The inductance of a SMD choke coil using the glassy $Fe_{77}P_{10.5}B_{9.5}Nb_2Cr_1$ alloy powder is 0.38 μH, 0.42 μH 0.47 μH and using the crystalline $Fe_{85}Si_{9.5}Cr_{5.5}$ alloy powder is 0.41 μH. The core losses ($W$) of the glassy $Fe_{97-x-y}P_xB_yNb_2Cr_1$ alloys and the amorphous $Fe_{75}Si_{10}B_{12}Cr_3$ alloy were measured under a frequency of 300 kHz and a field of 50 mT with B-H loop analyzer for the ring core shape after annealing of 623 K. The crystalline $Fe_{85}Si_{9.5}Cr_{5.5}$ alloy is after annealing of 423 K. The efficiency of SMD choke coil of the glassy $Fe_{77}P_{10.5}B_{9.5}Nb_2Cr_1$ was measured by a voltage step down DC/DC converter evaluation board of MAXIM 1717 evolution kit, input voltage of 12.0 V, output voltage of 1.0 V and frequency of 300 kHz after annealing of 623 K. The SMD choke of the crystalline $Fe_{75}Si_{10}B_{12}Cr_3$ alloy was measured with same condition after annealing of 423 K.

## 3. Results and discussion

It is well known that many kind of soft-magnetic materials have used in inductor core material. The iron-based amorphous alloys are one of inductor materials having low core losses. Some kind of iron-metalloid amorphous alloys for inductor core materials have been developed and used in practical devices. Especially, Fe–Si–B–(Cr) amorphous alloy system is now a major material widely utilized for industrial products. But iron-based amorphous alloys are not used to the SMD choke coil material due to the higher annealing temperature of 773 K. Because insulating coating of inner-cupper wire in SMD choke coil is posed big damage with a higher annealing temperature of 773 K. Therefore, we focused on Fe-based glassy alloys [3] and developed the novel glassy alloy composition of Fe–P–B–Nb alloy system exhibiting high performance at the lower annealing temperature of 623 K [4].

Fig. 1 shows the compositional dependence of the maximum thickness for glass formation ($T_{max}$) of melt-spun $Fe_{97-x-y}P_xB_yNb_2Cr_1$ alloys. The glassy phase is obtained in a wide compositional range of over 100 μm lies in the enclosed range of 5–13 at% P, 7–15 at% B and 78–81 at% Fe + $Nb_2Cr_1$. In particular, the largest $T_{max}$ of 150 μm can be obtained in compositional range of $Fe_{97-x-y}P_xB_yNb_2Cr_1$ ($x$ = 5–8, $y$ = 12–15). Higher $T_{max}$ is a significantly important characteristic to produce powders for an inductor core, using water atomization.

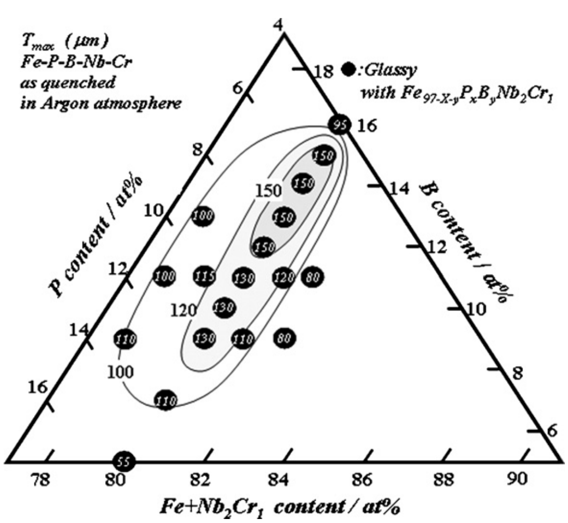


**Fig. 1.** The compositional dependence of the maximum thickness for glass formation ($T_{max}$) for melt-spun $Fe_{97-x-y}P_xB_yNb_2Cr_1$ alloys.

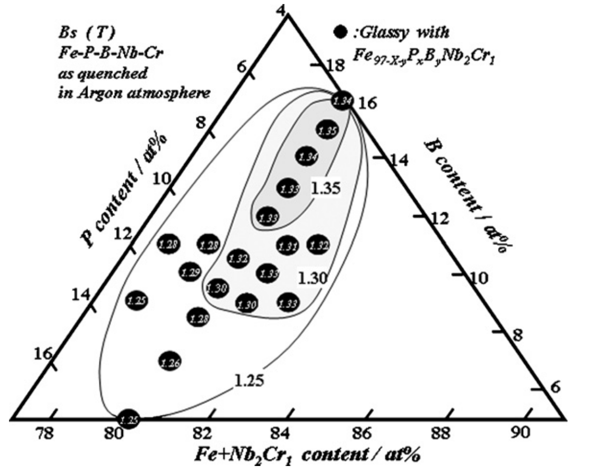


**Fig. 2.** The compositional dependence of the saturation magnetic flux density ($B_s$) for melt-spun $Fe_{97-x-y}P_xB_yNb_2Cr_1$ alloys.

Fig. 2 shows the compositional dependence of the saturation magnetic flux density ($B_s$) for glassy $Fe_{97-x-y}P_xB_yNb_2Cr_1$ alloys. The high $B_s$ of over 1.25 T is obtained in a wide compositional range of the enclosed range of 5–15 at% P, 5–16 at% B and 78–82 at% Fe + $Nb_2Cr_1$, as indicated with line of 1.25 T. The largest $B_s$ of 1.35 T can be obtained in compositional range of $Fe_{97-x-y}P_xB_yNb_2Cr_1$ ($x$ = 4–8, $y$ = 12–16).

Fig. 3 shows the phosphorus compositional dependence of melting point ($T_m$) and liquid phase point ($T_l$). $T_m$ and $T_l$ lowering trends with phosphorus content are significantly observed in a wide phosphorus range from 7.0 at% to 15.0 at%. Especially, $T_l$ is lowered in the upper range of 9.5 at% P. Therefore, we decided that the optimum composition for making powders in glassy $Fe_{97-x-y}P_xB_yNb_2Cr_1$ systems is $Fe_{77}P_{10.5}B_{9.5}Nb_2Cr_1$ due to low $T_m$ and $T_l$ one can obtain good spherical shape particles by water atomization. $Fe_{77}P_{10.5}B_{9.5}Nb_2Cr_1$ also exhibits high $B_s$ of 1.3 T.

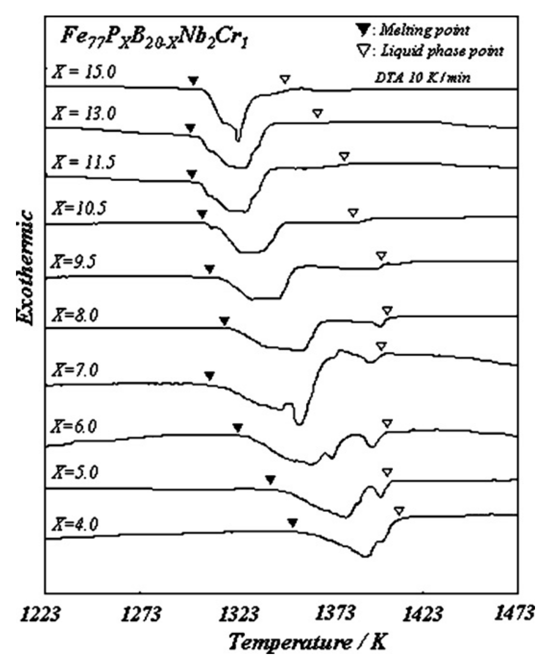


**Fig. 3.** The phosphorus composition dependence of melting point ($T_m$) and liquid phase point ($T_l$).

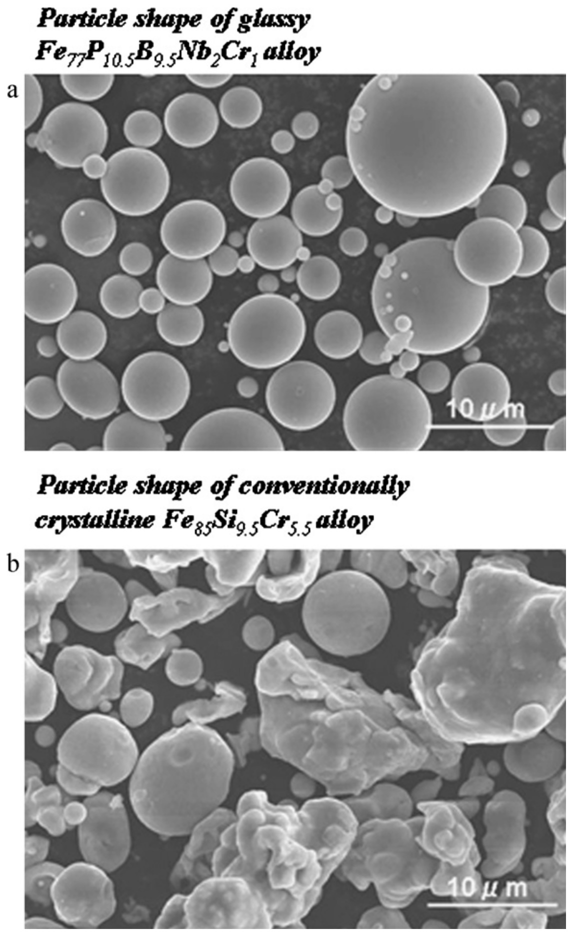


**Fig. 4.** SEM micrographs of particle shapes of the glassy $Fe_{77}P_{10.5}B_{9.5}Nb_2Cr_1$ and crystalline $Fe_{85}Si_{9.5}Cr_{5.5}$ alloy powders.

Fig. 4 shows SEM micrographs of the glassy $Fe_{77}P_{10.5}B_{9.5}Nb_2Cr_1$ and the crystalline $Fe_{85}Si_{9.5}Cr_{5.5}$ alloy powders. The glassy $Fe_{77}P_{10.5}B_{9.5}Nb_2Cr_1$ powder consists of much spherical particles than the crystalline $Fe_{85}Si_{9.5}Cr_{5.5}$ alloy powder having a higher $T_m$ of 1720 K and $T_l$ of 1752 K. On the other hand, the crystalline $Fe_{85}Si_{9.5}Cr_{5.5}$ alloy powder with high $T_m$ of 1720 K exhibits spheroidal particle shape is no good.

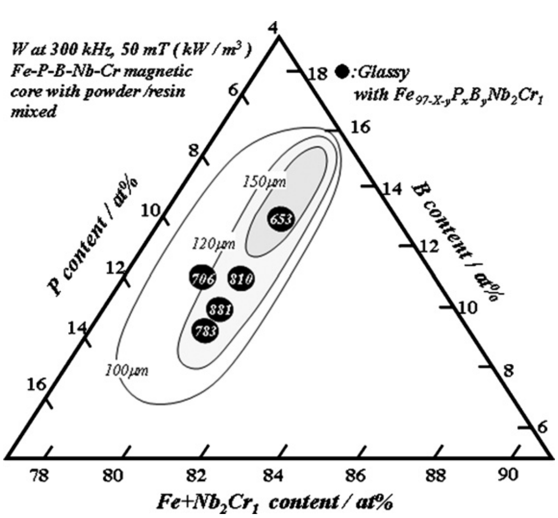


**Fig. 5.** The compositional dependence of core losses ($W$) for the glassy $Fe_{97-x-y}P_xB_yNb_2Cr_1$ alloys powder/resin composite core after annealing temperature at 623 K.

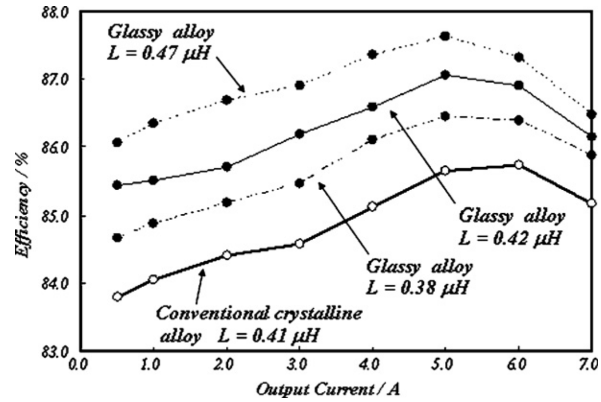


**Fig. 6.** The output current dependence of the power load efficiency for the glassy $Fe_{77}P_{10.5}B_{9.5}Nb_2Cr_1$ and crystalline $Fe_{85}Si_{9.5}Cr_{5.5}$ alloys SMD choke coils.

Fig. 5 shows the compositional dependence of core losses ($W$) for glassy $Fe_{97-x-y}P_xB_yNb_2Cr_1$ alloys powder/resin composite core after annealing temperature of 623 K. For 80 at% Fe + $Nb_2Cr_1$, excellent low core losses of 653–881 kW/m$^3$ are obtained in a wide compositional range of 7–11 at% P, and 9–13 at% B, as enclosed with in the line of 120 μm. This result is presumably the effect of the high glass formation resulting from the high stability of amorphous structure as evidenced from the existence of the super-cooled liquid region ($\Delta T_x$) of 35 K featuring the glassy alloy.

Fig. 6 shows the output current dependence of the power load efficiency for the glassy $Fe_{77}P_{10.5}B_{9.5}Nb_2Cr_1$ and the crystalline $Fe_{85}Si_{9.5}Cr_{5.5}$ alloy SMD choke coil. Generally, the efficiency of the inductor is indicated by the quality factor ($Q$) giving by the following formula:

$$Q = \frac{\omega L}{R}$$

here $Q$ is the quality factor, $\omega$ is the angular velocity, $L$ is the inductance, and $R$ is the magneto-resistance. It can be confirmed to the inductor that one with high inductance can obtain high efficiency from the above formula. However, the glassy $Fe_{77}P_{10.5}B_{9.5}Nb_2Cr_1$ alloy SMD choke coil with low inductance of 0.38 μH exhibits a higher efficiency compared with the crystalline $Fe_{85}Si_{9.5}Cr_{5.5}$ alloy SMD choke coil with high inductance of 0.41 μH. For the glassy $Fe_{77}P_{10.5}B_{9.5}Nb_2Cr_1$ alloy SMD choke coil with an inductance of 0.42 μH, one can achieve a higher efficiency of approximately 2.0% compared with the crystalline $Fe_{85}Si_{9.5}Cr_{5.5}$ alloy SMD choke coil of 0.41 μH. Thus, the high efficiency of SMD choke coil can be obtained by using the glassy $Fe_{77}P_{10.5}B_{9.5}Nb_2Cr_1$ alloy powders which named "*SENNTIX*". *SENNTIX* is a registered trademark for the glassy $Fe_{77}P_{10.5}B_{9.5}Nb_2Cr_1$ alloy powder.

Table 1 summarizes $T_c$, $T_g$, $T_x$, $\Delta T_x$, $T_m$, $T_l$ and $T_{max}$, magnetic properties ($B_s$, $H_c$) and core losses ($W$) for the glassy $Fe_{97-x-y}P_xB_yNb_2Cr_1$ alloys, amorphous $Fe_{75}Si_{10}B_{12}Cr_3$ and crystalline $Fe_{85}Si_{9.5}Cr_{5.5}$ alloys. Here, $T_{max}$ is applied as the parameter for GFA. The glassy $Fe_{97-x-y}P_xB_yNb_2Cr_1$ alloys have fairly larger $T_{max}$ of 110–150 μm compared with the amorphous $Fe_{75}Si_{10}B_{12}Cr_3$ alloy without glass transition. This is consistent with the appearance of super-cooled liquid region with $\Delta T_x$ of 29–37 K. The glassy $Fe_{97-x-y}P_xB_yNb_2Cr_1$ alloys exhibit relatively high $B_s$ of 1.26–1.33 T in comparison with the amorphous $Fe_{75}Si_{10}B_{12}Cr_3$ alloy with high Fe content. Additionally, this novel glassy $Fe_{97-x-y}P_xB_yNb_2Cr_1$ alloy has much lower core loss characteristics due to having lower $H_c$ than the ordinary amorphous $Fe_{75}Si_{10}B_{12}Cr_3$ alloy. Hence one can conclude that the glassy $Fe_{97-x-y}P_xB_yNb_2Cr_1$ alloy is only one glassy alloy system of very few Fe-based glassy alloys with having both

**Table 1**
The Curie temperature ($T_c$), glass transition temperature ($T_g$), crystallization temperature ($T_x$), melting temperature ($T_m$), liquid phase point ($T_l$), the parameter of glass-forming ability ($\Delta T_x$, $T_{max}$) and the magnetic properties ($B_s$, $H_c$) and core losses ($W$) for $Fe_{(97-x-y)}P_xB_yNb_2Cr_1$ glassy alloys, typical Fe-based amorphous alloy and the conventional crystalline alloy.

| Characteristic material | $T_c$ (K) | $T_{\varepsilon\cdot}$ (K) | $T_x$ (K) | $\Delta T_x$ (K) | $T_m$ (K) | $T_l$ (K) | $T_{max}$ (mm) | $B_s$ (T) | $H_c$ (A/m) | $W$ (kW/m$^3$) | Formation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $Fe_{77}P_7B_{13}Nb_2Cr_1$ | 556 | 767 | 795 | 36 | 1317 | 1402 | 150 | 1.33 | 2.5 | 653 | Glass |
| $Fe_{77}P_9B_{11}Nb_2Cr_1$ | 553 | 759 | 789 | 31 | 1315 | 1403 | 130 | 1.33 | 2.5 | 810 | Glass |
| $Fe_{77}P_{10.5}B_{9.5}Nb_2Cr_1$ | 544 | 750 | 785 | 35 | 1308 | 1396 | 130 | 1.30 | 3.8 | 881 | Glass |
| $Fe_{77}P_{11}B_9Nb_2Cr_1$ | 549 | 754 | 783 | 29 | – | – | 130 | 1.30 | 2.5 | 783 | Glass |
| $Fe_{77}P_{11}B_7Nb_2Cr_1$ | 536 | 740 | 771 | 37 | 1306 | 1366 | 110 | 1.26 | 3.1 | – | Glass |
| $Fe_{76}P_{10}B_{11}Nb_2Cr_1$ | 554 | 762 | 793 | 31 | – | – | 115 | 1.28 | 2.8 | 706 | Glass |
| $Fe_{75}Si_{10}B_{12}Cr_3$ | 648 | – | 848 | – | 1435 | 1469 | 50 | 1.25 | 14.8 | 1989 | Amorphous |
| $Fe_{85}Si_9Cr_6$ | 964 | – | – | – | 1720 | 1752 | – | 1.65 | 44.0 | 2361 | Crystalline |

$H_c$ and $W$ are after annealing at 623 K.

high $B_s$ and low core loss at lower annealing temperature [5,6]. Furthermore, the glassy $Fe_{97-x-y}P_xB_yNb_2Cr_1$ alloys with low $T_m$ and $T_l$ are suitable for producing powders consist of spherical particles to be used in inductor cores.

## 4. Conclusions

1. The large $T_{max}$ of over 100 μm was obtained in 5–13 at% P, 7–15 at% B and 78–81 at% Fe + $Nb_2Cr_1$. The largest $T_{max}$ of 150 μm was achieved in the composition range of $Fe_{97-x-y}P_xB_yNb_2Cr_1$ ($x$ = 5–8, $y$ = 12–15).
2. High $B_s$ of 1.35 T was also obtained for the glassy $Fe_{97-x-y}P_xB_yNb_2Cr_1$ ($x$ = 4–8, $y$ = 12–16) alloys.
3. Low $T_m$ and $T_l$ were obtained for the glassy $Fe_{77}P_xB_{20-x}Nb_2Cr_1$ ($x$ = 7–15) alloys, and $Fe_{77}P_xB_{20-x}Nb_2Cr_1$ ($x$ = 7–15) alloys were exhibited to the optimum soft-magnetic material for a powder of an inductor core.
4. The excellent high efficiency of approximately 2.0% with the SMD choke coil were attained for the glassy $Fe_{77}P_{10.5}B_{9.5}Nb_2Cr_1$ alloy to leading in conjunction with the minimum value of core loss of 881 kW/m$^3$.

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