Cast iron (CI) based soft magnetic BMG \( \text{Ci}_{88.3}\text{Al}_2\text{Ga}_1\text{P}_{4.35}\text{B}_{4.35} \)

S. N. Kane\(^1\), H. J. Lee\(^1\), Y. H. Jeong\(^1\) and L. K. Varga\(^3\)

\(^1\)Department of Physics, Pohang University of Science and Technology (POSTECH), 790-784 Pohang, South Korea
\(^2\)On leave from: School of Physics, D. A. University, Khandwa road Campus, Indore-452017, India
\(^3\)RISSPO, Hungarian Academy of Sciences, P.O. Box 49, 1525 Budapest, Hungary

e-mail for correspondence: varga@szfki.hu (L.K. Varga)

Abstract. Thermal stability, structure, and magnetic properties of bulk type \( \text{Ci}_{88.3}\text{Al}_2\text{Ga}_1\text{P}_{4.35}\text{B}_{4.35} \) alloy in ribbon form have been studied using differential thermal analysis, x-ray diffraction and magnetic measurements. Results reveal that crystallization peak temperature \( T_x \) and Curie temperature \( T_C \) of the as-cast alloy are respectively 513 and 370 \(^\circ\)C. Crystallization of the specimen starts after annealing at 460 \(^\circ\)C and \( \alpha\)-Fe is precipitated out. Annealing at temperatures higher than 515 \(^\circ\)C, produces apart from \( \alpha\)-Fe, hard magnetic precipitants (Fe\(_2\)B, Fe\(_3\)B), which deteriorate the soft magnetic properties. Lowest coercive field - 9.8 A/m, highest saturation of induction - 1.55 Tesla and best losses – 0.42 W/kg (at 50 Hz and 0.4 kA/m) were obtained for as-cast specimen. Observed good soft magnetic properties of these low cost cast-iron based alloys suggest perspective applications of these soft magnetic alloys as an alternative to the conventional Fe-Si electrical steel and Mn-Zn ferrites.

1. Introduction
Multi-component bulk type amorphous alloys exhibiting large glass forming region, good soft magnetic properties, excellent mechanical properties and corrosion resistance have attracted researchers due to their applications as soft magnetic and structural materials [1,2]. In this context bulk type multi-component Cast iron (Ci) based alloys have emerged as cheap soft magnetic materials which can either be cast in ribbon shape or in cylinders with transversal dimensions of up to several mm [3]. Studying the structure, stability and soft magnetic properties of these cheap alloys the application of them as transformer sheets of 0.2-0.5 mm thick instead of non-oriented Fe-Si sheets will be prospected.

In the present work we report the structural and magnetic investigation of multi-component bulk type \( \text{Ci}_{88.3}\text{Al}_2\text{Ga}_1\text{P}_{4.35}\text{B}_{4.35} \) alloy obtained by adding minimal amount of glass forming elements (B, P, Al and Ga) to the cast iron to turn it into a bulk glass and to preserve the high saturation induction.

2. Experimental
Ribbon of nominal composition \( \text{Ci}_{88.3}\text{Al}_2\text{Ga}_1\text{P}_{4.35}\text{B}_{4.35} \) (where \( \text{Ci} = \text{Fe}_{81.5}\text{Si}_{1.77}\text{C}_{13.9}\text{Mn}_{0.67} \)), about 35 µm thick and 4 mm wide was prepared using a planar flow casting technique on copper wheel with 33 m/s tangential velocity. Thermal stability was examined by Differential Thermal Analysis (DTA) measurements performed at a heating rate of 20 K/min. DTA measurements (depicted in figure 1 a)
shows a glass transition at Tg ~ 426 °C and a crystallization peak (Tx) at 513 °C. Specimens were annealed in the inert atmosphere of flowing Ar at 460, 515 and 600 °C for 10 min., which are respectively below, at and above the crystallization peak. XRD measurements were done using Cu-Kα radiation at room temperature. High field hysteresis loops of all the samples were measured using a Quantum Design Physical Property Measurement System (PPMS) vibrating sample magnetometer (VSM) option with a maximum field of ±500 Oe (= ±40 kA/m), were used to obtain saturation induction (B_s). In order to convert emu/g to Tesla we have used average density value of 7.2 g/cm³ for the studied specimen. In this way the VSM data (emu/g) can be compared with those determined by inductive methods (Tesla). Error in the estimation of B_s values could be of the order of 6 %. Temperature dependent magnetization was measured using PPMS up to 900 K to obtain Curie temperature of the as-cast specimen. Low field hysteresis loops for as cast and annealed (460 °C / 10 min.) samples were recorded at 50 Hz using a hysteresis loop tracer based on a 16-bit digital storage oscilloscope. The coercive field (Hc) and losses were determined at a maximum applied field of ±0.32 kA/m.

3. Results and discussions
Figure 1(a) depicts the DTA curve and the characteristic temperatures Tg, Tx1 and Tx2 are 426, 496 and 513 °C, respectively. Figure 1(b) depicts the temperature dependent magnetization curve showing that the Curie temperature of the as-cast specimen is 370 °C. It is worth mentioning that there is a strong overlapping two step crystallization (see the insert of Fig.1a) so the primary precipitation of the majority element (Fe) can be expected by annealing in the supercooled liquid region (Tg < Tann < Tx1 only.

Figure 2 depicts the annealing temperature evolution of structure as reflected in the X-ray diffractograms (left panel) and magnetic properties (right panel). Table 1 depicts the coercive field \( H_c \), saturation induction \( B_s \), and losses. For comparison, the values of \( B_s \), \( H_c \) and losses for a Fe-based NANOPERM type nanocrystalline alloy [4,5 and 6] are also given. Perusal of figure 1(left panel) shows that crystallization of the specimen starts after annealing at 460 °C and α-Fe is precipitating out. Annealing temperatures higher than 515 °C, apart from α-Fe, hard magnetic precipitants (Fe₂B, Fe₃B) deteriorate the soft magnetic properties (Hc increases sharply) as can be seen very clearly in the hysteresis loops of figure 2 (right panel). Perusal of table 1 shows that thermal annealing does not improves the magnetic properties especially the magnetic properties are adversely affected after annealing at temperature higher then Tx. The smallest coercive field \( H_c \) of 9.9 A/m was obtained for the as-cast specimen. The technical saturation induction \( B_s \) values for the annealed samples are varying between 1.12 to 1.55 Tesla and the highest value of 1.55 Tesla is obtained again for the as-cast specimen. The as cast and the specimen annealed at 460 °C for 10 min. reveal relatively
low losses at 50 Hz and 0.32 kA/m (see Table 1), comparable with that of the Zr containing Nanoperm
type nanocrystalline alloy.

Figure 2. Annealing temperature evolution of structure and magnetic properties.

Observed good soft magnetic properties of these low cost cast iron based alloys prepared with industrially available cheap materials are suitable for various applications as soft magnetic alloys and can be an alternative to the conventional Fe-Si electrical steel. Low field hysteresis loops for as-cast and annealed (at 460 °C/10 min) specimens are depicted in fig. 3. Interestingly, a pretty linear (flat) loop with an effective permeability of 2200 was obtained for the sample at the incipient stage of crystallization without mechanical stress or magnetic field annealing. This is probably due to stress induced by the surface crystallization. Such a flat loop is desirable for power electronics applications to replace Mn-Zn ferrites. So not only Fe-Si but ferrites can be replaced by the studied materials, where there is no size limit, one can make filter cores wound from amorphous ribbon of desired dimensions (e.g., - even 1 m diameter) which can withstand with the DC bias current and it is proposed to be used in the wind generators and in electric locomotives.

Table 1. Magnetic properties of the studied samples, where \( B_s \): technical saturation, \( H_c \): coercive field

| Specimen           | \( B_s \) (emu/g)/(Tesla) | \( H_c \) (A/m) | Losses (W/kg) (At 50 Hz and 0.32 kA/m) (W/kg) |
|--------------------|---------------------------|---------------|-----------------------------------|
| As-cast amorphous  | 171.3 / 1.55              | 9.8           | 0.42                              |
| Ann. 460 °C/10 min | 167.7 / 1.52              | 12.9          | 0.54                              |
| Ann. 515 °C/10 min | 132.0 / 1.19              | 7222.5        | —                                 |
| Ann. 600 °C/10 min | 123.3 / 1.12              | 7311.4        | —                                 |
| Nanoperm (nanocryst. alloy) | —— / 1.65          | 10.28         | 0.45                              |
4. Summary

DTA, XRD and magnetic measurements have been used to study cast-iron based bulk type \( \text{C}_{188.3}\text{Al}_{2}\text{Ga}_{1}\text{P}_{4.35}\text{B}_{4.35} \) alloy in ribbon form. Results show that: i) crystallization peak temperature and Curie temperature of the as-cast alloy are 513 and 370, respectively \( \text{C} \) \( ^\circ \), ii) crystallization of the as-cast specimen starts after annealing at 460 \( \text{C} \) and \( \alpha \)-Fe is precipitated out, iii) annealing at temperatures higher than 515 \( \text{C} \), apart from \( \alpha \)-Fe, produces hard magnetic precipitants (Fe\(_2\)B, Fe\(_3\)B) which deteriorates the soft magnetic properties., iv) the best properties were obtained for the as-cast specimen: coercive field - 9.8 A/m, technical saturation - 1.55 Tesla and losses – 0.42 W/kg (at 50 Hz and 0.32 kA/m). The good soft magnetic properties of these low cost cast-iron based alloys permit their applications as transformer sheet replacing the conventional Fe Si electrical steel and as inductive elements in power electronics applications, replacing Mn-Zn ferrites.

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References
[1] Inoue A, Shen B L, Koshiba H, Kato H and Yavari A R, 2004 Acta Mater. 52 1631
[2] Qin C., Zhang W, Asami K, Ohtsu N and Inoue A, 2005 Acta Mater. 53 3903
[3] Inoue A and Wang X M, 2000 Acta Mater. 48 1383
[4] Makino A, Hatanai T, Naitoh Y, Bitoh T, Inou, A and Masumoto T, 1997 IEEE Trans. Magn. 33 3793
[5] Modak S S, Ghodke N, Mazaleyrat F, Lo Bue M, Varga L.K, Gupta A. and Kane S N, 2008 J. Magn. Magn. Mater. B e828
[6] Ohta M and Yoshizawa Y, 2007 Jpn. J. Appl. Phys. 46 L477