Fe-Based Magnetic Amorphous Alloys

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Amorphous alloys for soft magnetic applications are often fabricated by rapid solidification of the melt. They are generally prepared with the nearly 20% addition of metalloids (Si, B, Al, C and P) for Fe-based and Co-based alloys. Si and B are important metalloids for glass formation and the amorphous structure stabilisation. Typical chemical compositions are such that the combined compositions of Fe, Co, Ni elements are 70–85 atomic (at.)% and those of Si and B are 15–30 at.% in total. However, magnetic glassy alloys have a wide variety of compositions. This allows for a large range of soft magnetic properties to be achieved, which depend upon the demands of the application.

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1. Introduction

In magnetic amorphous alloys, the microstructure lacks atomic long-range order and only exhibits short-range order, which is essentially random atomic arrangement of the liquid melt solidified at a cooling rate of 10^5–10^6 K/s. As a result, there are no crystallite-related defects including grain boundaries and dislocations, leading to a decrease in coercivity (see Figure 1) [1].

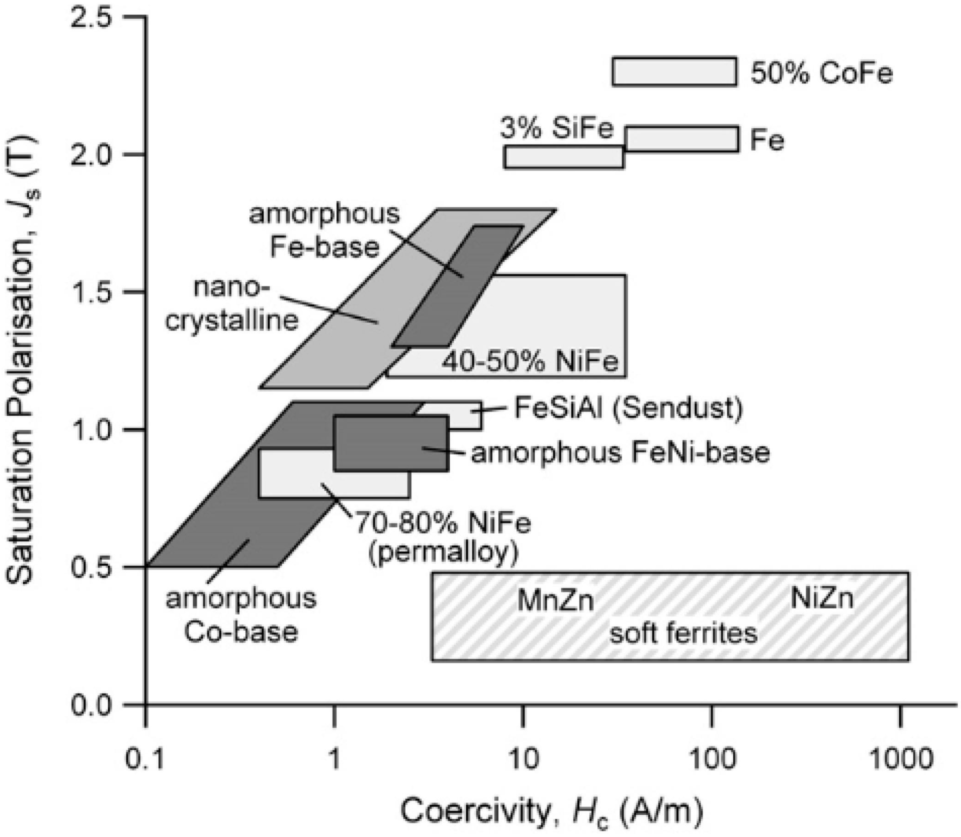

Figure 1. Comparison of the magnetic properties of soft magnetic materials (reprinted with the permission from [2], Elsevier, 2013).

Amorphous Fe-based alloys, based on inexpensive raw materials, have relatively high saturation magnetisation (see Figure 1) and high magnetostriction [2], which makes them promising candidates for sensors and actuators [3][4][5][6][7].

Figure 2 illustrates the relationship between the saturation magnetostriction constant and Si content for the FeCuNbSiB alloy system. The saturation magnetostriction (λ_S) has the highest value and is virtually independent of Si composition for the amorphous structure, different from the nanocrystalline state where magnetostriction is significantly dependent on the Si concentration and its maximum value is as nearly half that of the amorphous structure.

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Figure 2. The saturation magnetostriction constant (λ_S) of $Fe_{96-z}Cu_1Nb_3Si_xB_{z-x}$ alloys as a function of Si content for the amorphous and nanocrystalline states (reprinted with the permission from [2], Elsevier, 2013).

Figure 3 indicates the change in the saturation polarisation (J_S) and the saturation magnetostriction constant (λ_S) of amorphous magnetic alloys as a function of Fe, Ni and Co content. Fe-rich alloys possess the highest saturation polarisation and saturation magnetisation constant, decreasing as Co and Ni concentration increases. J_s for amorphous materials is usually lower than polycrystalline ones (Figure 1) because of the addition of nonmagnetic metalloids (Si and B) required for glass formation [2].

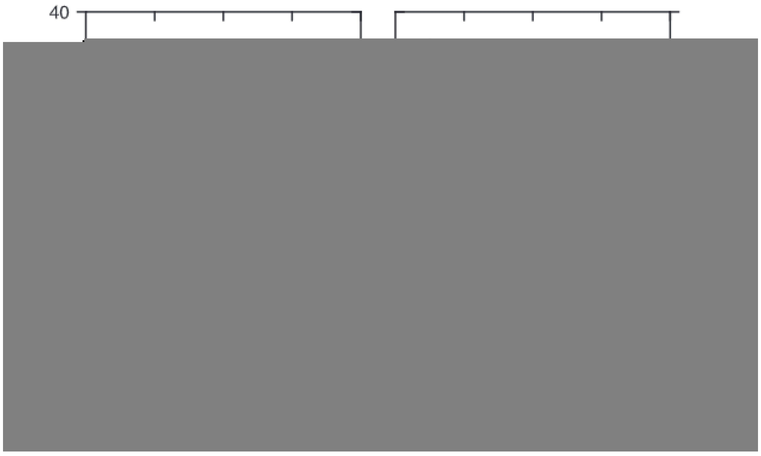

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Figure 3. Saturation magnetisation J_s (dashed lines) and saturation magnetostriction λ_s (full lines) of amorphous Fe-Ni-based and Fe-Co-based alloys with changing Ni and Co content, respectively (reprinted with the permission from [2], Elsevier, 2013).

The saturation magnetostriction of Fe-based amorphous alloys is typically positive, ≈ 20–40 ppm, on the other hand for Co-based amorphous alloys, it is typically negative, ≈−5 to −3 ppm. The increase in λ_s with lowering Ni concentration is linked to a concurrent increase in J_s ($|\lambda s| \propto J2s$). Therefore, near zero λ_s at high Ni concentrations only occur as the system becomes paramagnetic [2].

Fe-B alloys with a saturation flux density higher than 1.5 T were the first metallic glass developed for the fabrication of distribution transformers. The addition of Si gave a higher thermal stability without any reduction in the saturation flux density, producing the ternary alloy $Fe_{82}B_{12}Si_6$. However, this is prone to material oxidation due to air pockets forming during the production process, lowering magnetic flux density and increasing total losses. $Fe_{81.5}B_{13.5}Si_3C_2$ was developed to overcome these limitations [8].

Fe-Si-B glassy alloys possess six times fewer energy losses than traditional Fe-Si alloys at industrial frequencies. In fact, $Fe_{79}B_{13}Si_8$ has a higher Curie temperature without changing core losses and flux density, compared with Fe-3%Si alloys in the fabrication of power transformers [8]. Therefore, they are competitive for applications where Fe-Si alloys are traditionally used.

After rapidly quenching of amorphous alloys, internal residual stresses are developed in the structure, altering the magnetic behaviour (increasing coercivity and reducing permeability) due to the emergence of magnetocrystalline anisotropy. Strain relief annealing has been employed below the crystallisation temperature not only to achieve higher permeability, lower energy losses and smaller coercivity (see Table 1), but also to improve mechanical properties by allowing atomic arrangement over a short distance. Table 1 clearly shows that although as-cast alloys exhibit very soft magnetic behaviour, strain relief annealing considerably allows the enhancement of magnetic properties (reducing coercivity, increasing permeability) by reliving the internal residual strains. Amorphous alloys with a wide variety of magnetic properties can be fabricated by annealing in the existence of an applied magnetic field [9].

Table 1. Magnetic properties of amorphous alloys under direct current (DC) applications (reprinted with the permission from [9], CRC Press, 2016).

		As Cast			**Annealed**		
Alloy	**Shape**	H_c **(A/m)**	M_r/M_s	μ_{max} **(10^3)**	H_c **(A/m)**	M_r/M_s	μ_{max} **(10^3)**
$Fe_{80}B_{20}$	Toroid	6.4	0.51	100	3.2	0.77	300
$Fe_{40}Ni_{40}P_{14}B_6$	Toroid	4.8	0.45	58	1.6	0.71	275
$Fe_{29}Ni_{44}P_{14}B_6Si_2$	Toroid	4.6	0.54	46	0.88	0.70	310
$Fe_{4.7}Co_{70.3}Si_{15}B_{10}$	Strip	1.04	0.36	190	0.48	0.63	700
$(Fe_{0.8}Ni_{0.2})_{78}Si_8B_{14}$	Strip	1.44	0.41	300	0.48	0.95	2000
$Fe_{80}P_{16}C_3B$	Toroid	4.96	0.4	96	4.0	0.42	130

There are a few limitations of using amorphous magnetic materials in certain applications. Firstly, their low saturation magnetisation restricts their usage in heavy current density engineering. Secondly, their core losses start to rise rapidly at high flux densities. For this reason, they have more use in low-power, low-current applications and specialised small-device applications where transformers are required with moderate flux densities. In these applications, amorphous magnetic materials can be used successfully instead of nickel-iron alloys including permalloy. Amorphous magnetic materials, being manufactured in large quantities, have been utilised in pulsed-power transformers, magnetic sensors, magnetostrictive transducers and communication equipment [9].

2. Importance of Fe-Based Magnetic Amorphous Alloys

Functional magnetic materials (FMMs) have gained considerable interest for advanced engineering devices owing to their technical benefits for energy conversion, harvesting, transmission, sensing/actuation [1], and more recently for magnetic refrigeration applications, based on their magnetocaloric effects [10]. Fe-based soft magnetic materials are of great importance for sensors, transformers, and inductive devices because of their superior magnetic properties such as outstanding magnetic permeability, low coercivity, and good corrosion resistance [11][12][13][14].

In general, Fe-based soft magnetic alloys are used in two distinct categories of applications:

- For producing and utilising electromagnetic energy: due to their low cost and ecological reasons, the usage of soft magnetic materials comprises an important part of these applications because they have high magnetic permeability, low energy losses and high magnetic saturation. Fe-Si-based alloys are considered as the most representative materials for this area.
- For signal processing: Fe-Ni-based alloys are usually used in informatics, electronics, transducers, magnetic recording heads, microwave installations and so on [7].

In the last two decades, significant progress has been achieved in the understanding of alloy design in an attempt to enhance the glass forming ability (GFA) of soft magnetic amorphous materials [15]. Therefore, many new bulk amorphous alloys with large GFA and good magnetic properties have been reported [16][17][18][19][20][21]. Casting methods including injection moulding have been used for the production of magnetic bulk metallic glasses (BMG). Zhang and his team utilised casting technique to fabricate glassy toroidal cores having good magnetic properties [22]. They consisted of $Fe_{66}Co_{10}Mo_{3.5}P_{10}C_4B_4Si_{2.5}$ BMG with an outer diameter of 10 mm and inner diameter of 6 mm, and showed low coercivity (1.0 A/m), high maximum magnetic permeability (450,000), low core loss (0.4 W/kg at 50 Hz) and maximum magnetic flux density (1 T) [22]. Nevertheless, dimensional limitations and poor mechanical properties restrict the use of casting techniques in the production of bulk metallic alloys.

Alternatively, to manufacture three-dimensional (3D) amorphous magnetic parts, powder metallurgy (PM), especially hot pressing and spark plasma sintering, has been extensively exploited [23][24][25]. To reduce the possibility of the deterioration of magnetic softness because of partial crystallisation in the amorphous matrix, it is necessary that consolidation behaviour and thermal stability of the glassy structure at elevated temperatures is controlled [26]. It is promising that the limitations of conventional techniques can be overcome by using additive manufacturing (AM) in the production of glassy magnetic alloys.

3. Conclusions

The literature demonstrates that laser additive manufacturing, which contains directed energy deposition and powder-bed fusion, is a promising process to produce Fe-based glassy alloys with good soft magnetic properties. The selective laser melting (SLM) technique from the powder-bed fusion category and the laser engineered net shaping (LENS) technique from the directed energy deposition category have been used for that purpose within the literature, resulting from their high availability, low cost and being less time-consuming compared with the conventional techniques that have been used to produce amorphous alloys, such as casting. In both techniques, amorphous alloys were manufactured by altering the process parameters. Generally, low energy input, achieved via low laser power and high laser scanning speed, brings about increased amorphous phase content due to a higher cooling rate, but decreases relative density and deteriorates mechanical properties. To overcome this limitation, the double scanning (remelting) strategy has been employed, which results in enhancing both magnetic and mechanical properties. Additionally, in the LENS process, it is also necessary to consider the substrate/prior deposit temperature, to ensure that it is kept as low as possible to obtain a high cooling rate. SLM has been utilised more than LENS in the fabrication of Fe-based amorphous alloys, since LENS is not preferred for the production of small parts because of low geometric accuracy and poor surface quality. This contradicts with the size limitation of glassy alloys owing to their high critical cooling rates.

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