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Development of New Amorphous and Nanocrystalline Magnetic Materials for Use in Energy-Efficient Devices

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ABSTRACT

Fe-based amorphous and nanocrystalline soft magnetic alloys have been intensively researched for many applications, including high efficiency electrical distribution and power conditioning applications. New amorphous foils with a saturation magnetization of 1.63T and new nanocrystalline foils with saturation up to 1.9T have been developed. Often these new materials are not drop-in replacements for the conventional competing alloys and require significant changes in processing to be able to fabricate commercial devices.

INTRODUCTION

Fe-based amorphous and nanocrystalline soft magnetic alloys are commonly used in many industrial products [1, 2]. This overview focuses on planar flow melt spun Fe-based amorphous ribbon and the precursor amorphous ribbon that is annealed into the nanocrystalline state. Energy efficient transformers are the largest volume application for Fe-based amorphous ribbon. The ductile amorphous ribbons are stacked, cut to length and formed into a wound laced distribution transformer core. Many studies have focused on the optimum conditions to minimize the core loss deterioration and excitation power associated with forming and annealing the cores [3, 4].

Nanocrystalline alloys are emerging as the premier products for medium to high frequency applications such as saturable reactor cores, inductors and switch-mode power supplies [5]. Nanocrystalline devices are made from ribbon that is typically cast fully amorphous and then formed into a tape wound or block core form. The core is annealed to achieve the nanocrystalline structure and then typically impregnated with glue after annealing [6]. The mechanical brittleness of the ribbon after the nanocrystallization step prevents one from annealing the ribbon first and then forming it into a core. Recent work has looked into forming the nanocrystalline ribbon and then crushing it for powder or flake based core applications [7].

ADVANCED AMORPHOUS ALLOYS

The commercially available Metglas®2605SA1 alloy has long been used in high efficiency transformers and other power electronic applications. The ribbon has a saturation induction of 1.56 T and most transformers designed with it have an operating induction of 1.35 T. Si-steel laminations have higher saturation induction levels (~1.8-2.0 T) but also have higher core losses. FeCo based amorphous alloys have saturation levels of 1.8 T but they are prohibitively expensive as a transformer core material. Table 1 shows the typical magnetic properties of various amorphous and nanocrystalline alloys compared with oriented Si-steel. The core losses depend on frequency and induction levels. Typical induction levels for each alloy are listed at 60 Hz conditions. (Note that the high saturation nanocrystalline alloy is not commercially available today and the properties are given elsewhere [8].) While the coercivity and core losses of an amorphous transformer are only a fraction of a similarly rated Si-steel based transformer, the lower operating induction requires a larger core size. The footprint of an amorphous transformer has historically been larger than a conventional transformer [9].

Table 1: Magnetic properties of various amorphous and nanocrystalline alloys compared with M3 Si-steel.

Metglas Alloy Designation	Saturation Induction (T)	Coercivity (A/m)	Core loss, 60 Hz (W/kg)	Stacking factor (%)	Chemistry
2605SA1	1.56	1.2	0.25 @ 1.35 T	88	FeBSi
2605HB1M	1.63	1.1	0.30 @ 1.42 T	89	FeBSi
2605CO	1.8	3.0	0.7 @ 1.6 T	85	FeCoBSi
FT-3W	1.2	1.0	0.05 @ 1.0 T	75	FeBSiNbCu
Other alloys					
M3 Si-steel	2.0	6.9	1.54 @ 1.7 T	96	FeSi
High Sat Nano*	1.75	3	0.3 @ 1.5 T	85	FeBSiCu

The stacking factor of Si-steel laminations can be near 96% due to the many rolling stages required to reduce the material thickness. Amorphous ribbon is directly cast from the molten stage to the rapidly quenched 25 micron thick ribbon and is not subsequently rolled thinner. The stacking factor of an amorphous core is determined by the flatness of the ribbon and the surface roughness of the ribbon in the as-quenched state. The first generation amorphous ribbons had stacking factors near 80% which again require a larger overall sized core.

Two recent trends have changed with Fe-based amorphous ribbon that helps to reduce the core size and overall transformer size. The first is a continuous improvement of the stacking factor of the ribbon from the first generation ribbons. Today the stacking factor is near 90% for amorphous ribbon. This allows for more volume of core material to fit into a smaller size. The second factor is the introduction of the advanced amorphous Metglas®2605HB1M ribbon with a saturation induction of 1.63 T [10]. The higher saturation allows for a further reduction in the core size. Typically an HB1M based transformer has an operating induction level of 1.42 T. Figure 1a) shows the core loss as a function of flux density for SA1 and HB1M distribution transformer cores while Figure 1b) show the excitation power of the cores. Moving to the higher operating induction level of 1.42 T for HB1M cores slightly increases the core loss and the excitation power compared to the SA1 cores. Figure 2 shows the same data comparing an HB1M amorphous core to an M3 Si-steel core.

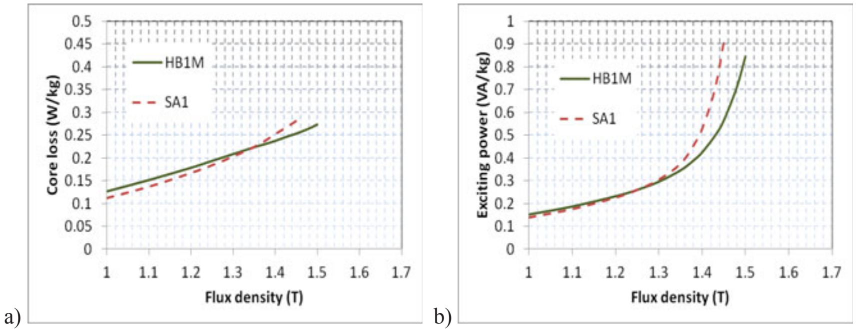

Figure 1: Typical values for a) core loss and b) excitation power for SA1 and HB1M based amorphous cores as a function of induction level while operating at 60 Hz.

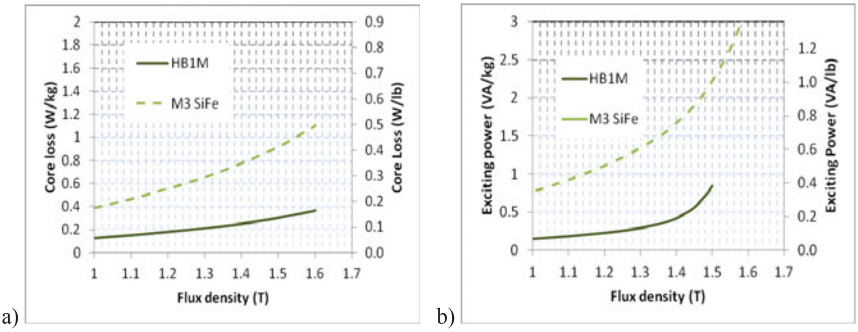

Figure 2: Typical values of a) core loss and b) excitation power for an M3 grade Si-steel core and an HB1M based amorphous core as a function of induction level while operating at 60 Hz.

ADVANCED NANO CRYSTALLINE ALLOYS

The conventional nanocrystalline alloys generally follow the FINEMET® chemistry of FeBSiNbCu. These alloys are cast as fully amorphous ribbons and then annealed through conventional methods to achieve the nanocrystalline structure [11]. The conventional process implies winding the ribbon into a toroid or tape wound core and then annealing in a furnace at a temperature above the onset crystallization event such that one achieves the desired nanocrystalline structure. The nanocrystalline electronic components have been available for many years but are currently being widely adopted commercially for emerging high frequency applications.

Recently, nanocrystalline ribbon has been produced domestically in the U.S. up to 142mm wide [12]. Traditionally FINEMET type ribbons have only been available at 60 mm in width. These ribbons are then slit to 10 or 20mm and wound into electric components. The wide nanocrystalline ribbon, Metglas®FT-3W, can be fabricated into much larger components that eliminate the need for multiple stacked core components for wide applications. Figure 3 shows a double stacked inductor core made from two tape wound cores of 142mm FT-3W ribbon. This unit is commercially available from MK Magnetics and is one of the largest nanocrystalline cores available today.

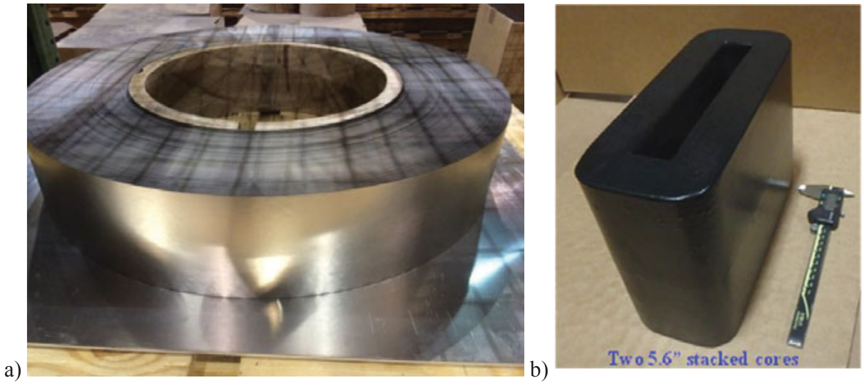

Figure 3: a) Full sized spool of 142mm (5.6”) wide FT-3W weighing 500 kgs and b) Inductor core fabricated from the 142mm nanocrystalline FT-3W ribbon.

The saturation induction of FINMET type alloys is limited to ~ 1.2 T in part because of the reduced Fe content inherent to the chemistry. This is above the level of many ferrites or Co-based amorphous alloys but significantly below Fe-based amorphous or Si-steels. The FINEMET chemistry includes Cu to help promote nucleation of the nanocrystalline phase during the furnace anneal and Nb to limit the grain growth to a uniform size distribution near 20 nm.

Many recent studies have focused on increasing the saturation induction to levels of 1.7 – 1.9 T of nanocrystalline alloys through a combination of chemistry modification and annealing conditions [8, 13-15]. The Fe content is increased by lowering the Nb content which helps to increase the induction level. The general chemistry for these higher induction level alloys is FeBSiCu with other trace elements. These alloys are cast into a fully amorphous state or may have nanocrystalline seed particles in the as-cast state. Then a rapid heat treatment is done to form the final nanocrystalline material.

The FINEMET ribbon can be formed into a tape wound core and annealed in a conventional furnace typically for one hour. The new nanocrystalline FeBSiCu type alloys require a high heating and cooling rate on the order of seconds to prevent the nanocrystalline phase from growing too large [5]. The high heating rates required results in the need for a new annealing method where the ribbon is heat treated and then wound into the core form. Typically this is done where the ribbon is wound in a reel-to-reel manner and passes through a heating unit such as a box oven. The high heating rates required are not possible to achieve when the material is wound into core form.

The high induction Fe-based nanocrystalline ribbon is typically mechanically brittle after it goes through the rapid annealing cycle. The brittleness limits the utility of the alloys for many tape wound applications. The brittle ribbon can be crushed into a powder form and many people are studying applications where amorphous or nanocrystalline powders are being processed into complex shapes [7, 16].

DISCUSSION

Fe-based amorphous alloys have been largely utilized in energy efficient transformers. However, the process of fabricating an amorphous transformer needed to be established before large scale commercialization was possible. The Fe-based amorphous ribbon is only 25 microns thick and more challenging to work with compared to Si-steel laminations. In forming an amorphous distribution transformer core, multiple plies (typically 15) of amorphous ribbon are fed into a cutting machine at the same time. The stack of ribbon is cut into multiple groups with increasing length increments to build an amorphous core. The cut ribbon can then formed into a laced core with distributed overlap joints that allow the core to open and close. The core is then heat treated under an applied magnetic field to induce longitudinal magnetic anisotropy. The core is reopened to apply the copper windings and closed again. Then the core-coil assembly can be processed into a final transformer following conventional methods.

The prescribed processing steps required in fabrication of an amorphous transformer are important. The core properties are not optimized if the forming steps or annealing conditions are not done properly leading to excessive core loss deterioration, high excitation power and audible noise that is higher than anticipated. The core forming process has become easier as the ribbon lamination factor has increased. The new HB1M alloy has a larger annealing temperature range that leads to optimum magnetic performance when compared with the SA1 alloy. The HB1M cores have also been shown to have lower audible noise than a similar SA1 core. These factors, coupled with the higher saturation induction of the HB1M alloy, have driven new growth in the amorphous transformer industry.

The advances in wide band gap semiconductors have driven new opportunities in high frequency power conversion. Many of the FINEMET type alloys are uniquely suited for these applications. The methods for producing the tape wound and glue impregnated nanocrystalline cores and components have been established. Tailoring the magnetic properties by magnetic field annealing is also common. Applications requiring very high permeabilities apply a longitudinal magnetic field during the anneal cycle by running a current through the center of the toroid. Applications requiring very low permeabilities apply a transverse magnetic field during the anneal cycle usually with a field set by hard magnets or by annealing within an induction coil.

Methods such as strain induced anisotropy can tailor the magnetic properties of these devices in ways that conventional field annealing cannot [5, 11]. Strain annealing (or tension annealing) can achieve even lower permeabilites than transverse field annealing in nanocrystalline alloys. However, the processing required to achieve strain induced anisotropy requires ribbon to be run through a furnace in a reel-to-reel manner. This unconventional annealing method has not been widely adopted commercially but it is an area of active research [17].

The new high induction nanocrystalline alloys that are being studied also commonly require a new annealing process involving high heating and cooling rates. This in turn requires the ribbon to be annealed directly rather than annealing a wound core. After annealing, the nanocrystalline ribbon is generally mechanically brittle to the point where a conventional tape wound core is very difficult to fabricate. New processing methods are being developed to handle the brittleness are being studied but few high induction nanocrystalline alloys have been commercialized today.

CONCLUSIONS

Progress in new amorphous magnetic alloys with higher saturation induction and higher stacking factor have led to smaller electrical distribution transformers that are economically competitive with Si-steel based transformers. The next generation of amorphous Metglas 2605HB1M foil is being adopted in distribution transformers globally. Nanocrystalline ribbons based on the FINEMET chemistry are increasingly being adopted as components for high frequency applications. New annealing methods are being developed to tailor the magnetic performance for specific applications. High induction nanocrystalline alloys have also been developed and the fabrication methods for integrating these alloys into electrical components are being studied.

REFERENCES

1. C. Smith, in *Rapidly Solidified Alloys*, edited by H. Liebermann, (Marcel Dekker, New Delhi, 1993) pp. 617-663.
2. R. Hasegawa, *J. Magn. Magn. Mater.*, 304, 187, (2006).
3. D. Li, L. Zhang, G. Li, Z. Lu, and S. Zhou, *Prog. Nat. Sci., Mat. Int.*, **22** 3, 244 (2012).
4. D. Raybould, M. Meola, R. Bye and S. Das, *Mat. Sci. Eng.*, A241, 191, (1988).
5. M. Willard and M. Danill, in *Handbook of Magnetic Materials, Vol 21*, edited by K. Buschow, (Elsevier, North Holland, 2013) pp. 173-342.
6. B. Cougo, A. Tuysuz, J. Muhlethaler and J. Kolar, in *Increase of Tape Wound Core Losses Due to Interlamination Short Circuits and Orthogonal Flux Components*, (IECON 2011, 37th Ann. Con. IEEE Ind. Ecect. Soc, 2011) pp. 1372-1377.
7. X. Wang, C. Lu, F. Guo, Z. Lu, D. Li and S. Zhou, *J. Magn. Magn. Mater.* 324, 2727, (2012).
8. M. Ohta and R. Hasegawa, IEEE Trans. Mag. 53, 2, (2017).
9. B. Kennedy, *Energy Efficient Transformers*, (McGraw Hill, New York, 1998), p. 127.
10. K. Takahashi, D. Azuma and R. Hasegawa, *IEEE Trans. Mag*. 49, 4001, (2013).
11. G. Herzer, in *Handbook of Magnetic Materials, Vol 10*, edited by K. Buschow, (Elsevier, North Holland, 1997) pp. 415-462.
12. High Performance Nanocrystalline Foil Product Release Sheet (2015). Available at: http://www.metglas.com/products/nanocrystallinefoil/... (accessed 2 May 2017).
13. M. Ohta, and Y. Yoshizawa, *J. Phys. D., App. Phys*, 44, 1, (2011).
14. P. Sharma, X. Zhang, Y. Zhang, A. Makinol, *Scripta Materialia*, 92, 6, (2015).
15. B. Zang, R. Parsons, K. Onodera, H. Kishimoto, A. Kato, A. Liu and K. Suzuki, *Scripta Materialia*, 132, 68, (2017).
16. H. Jung, M. Stoica, S. Yi, D. Kim and J. Eckert, *Met. Mat. Trans. A*, 45A, 2415, (2015).
17. A. Leary, P. Ohodnicki and M. McHenry, *JOM*, 64, 772, (2012).