Recent Progress in Fe-based nanocrystalline soft magnetic alloys and their applications

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More than 25 years have passed since Fe-Cu-Nb-Si-B nanocrystalline alloys which are typical alloys of FINEMET® had been discovered[1]. Fe-Cu-Nb-Si-B nanocrystalline alloys are formed to cores and the cores are used in current transformer for ground fault interrupters, common mode chokes (CMC) in EMI filter and high frequency transformers. This is because high permeability from low frequency up to 100 kHz, a high operating magnetic flux density B_{m} owing to relatively higher saturation magnetic flux density $B_{\mathrm{s}} \approx 1.2$ T than that of competitors and low core losses for example core loss at 0.2 T at 100 kHz, $P_{2/100\mathrm{k}} = 48$ W/kg.[1] For CMC core, there are requirements of downsizing of core as well as improvement of frequency dependence of impedance. Since amount of heat limits the B_{m}, and less core loss makes less heat especially in the high frequency transformers, further reduction of core loss enables to use in higher B_{m}, resulting in downsizing of core.

In electrical distribution transformers (50Hz / 60 Hz), also energy efficiency has to be improved considering increase of recent energy cost and requirement of CO_2 emission reduction. Fe-based amorphous alloy based transformers show much higher energy efficiency than that based on conventional grain-oriented silicon steel. However, because of low $B_{\mathrm{s}} \approx 1.6$ T, this is about 80% of grain-oriented silicon steel, physical size of Fe-based amorphous alloy based cores tends to be larger than that based on grain-oriented silicon steel when the same output of transformers was designed.[2,3] The reason is as follow; B_{m} in transformer cores is determined by core loss, noise, frequency and voltage fluctuation in transformers etc. Practically B_m is about 80 – 85% of B_s, thus B_m of grain-oriented silicon steel and Fe-based amorphous alloys based cores is limited around 1.6 - 1.7T and 1.3 - 1.45 T, respectively.

In this presentation, we would like to introduce our research and development to increase B_{m} of cores for both high and low frequency applications and new products based Fe-Cu-Nb-Si-B nanocrystalline.

Combination of thinner ribbon thickness (18 μm → 13 μm) and magnetic field annealing for Fe-Cu-Nb-Si-B nanocrystalline alloy improved frequency dependence of impedance and decrease core loss, and succeeded in developing new CMC cores (FT-3K50T) and high frequency transformer cores (FT-3TL) [4,5] .

For low frequency applications, we aimed to create an alloy with nanocrystalline phase with high Fe content. The concept of material design was to realize high B_{s} with high Fe content, bcc-Fe phase and excellent soft magnetic properties by randomness of nanocrystalline structure. By adding 1.5 at.% of Cu in basic Fe-B amorphous alloy system, precipitation of primary crystals at as-melt-spun state was confirmed. A nanocrystalline phase of average grain size of about 20 nm was obtained after annealing this ribbon at 390°C for 3.6 ks.[6]

The mixing heat of Fe and Cu is positive, and hence it suggests that in the quenching process, over saturation of Cu occurs in the supercooled glassy state and that results in the aggregation of Cu clusters. The Cu clusters help to nucleation of primary crystals and crystallization arose from primary crystals, and increase content of B in amorphous matrix lead to nanocrystalline structure resulting excellent soft magnetic properties without adding Nb. After the discovery of this material, further improvement of soft magnetic properties was made for $Fe_{\mathrm{bal.}}Cu_{1.4}Si_5B_{13}$ nanocrystalline alloy of which single strip ribbon exhibits core loss at 1.5 T at 50 Hz, $P_{15/50}$ of 0.29 W/kg, that is about one half of grain-oriented silicon steels, with B_{s} of 1.8 T, that is about 10% higher than that of Fe-based amorphous alloys.[6] However, due to primary crystals in as-melt-spun state, the ribbon is brittle and difficult to handle. To solve this issue, the perspiration of primary crystals at as-melt-spun state has to be avoided what is similar to conventional Fe-Cu-Nb-Si B alloys and/or Fe-M-B (M = transition metals) alloys. [1,7] These alloys exhibit amorphous phase in as-melt-spun state and become nanocrystalline phase by annealing.[1,7] Conventional Fe-based nanocrystalline alloys contain at least 2 at.% of a heavy non-magnetic element such as Nb, since decrease of them results in deterioration of soft magnetic properties when applying normal annealing , for example heating rate of 5 ^{o}C/min. Therefore their B_s is 1.2~1.7 T.[1,7] It is necessary to reduce the amount of Nb to increase B_s maintaining nanocrystalline structure. On the other hand, it is known that higher heating rate in annealing process brings about finer nanocrystalline structure.[8] With combining concepts of less Nb to achieve higher B_s and high heating rate annealing to achieve excellent soft magnetic properties, $Fe_{bal.}Nb_1Cu_1Si_4B_{12}$ alloy ribbon was developed. Single sheet of this alloy annealed with heating rate of more than 3^{o}C/s up to 450^{o}C exhibits B_s of 1.78 T and $P_{15/50}$ of 0.20 W/kg.[9] the cores made by this material has a high potential to become a next generation high B_m magnetic core not only for transformers but also for reactors and motors.

References

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