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Finemet nanocrystalline soft magnetic alloy: Investigation of glass forming ability, crystallization mechanism, production techniques, magnetic softness and the effect of replacing the main constituents by other elements

T. Gheiratmand, H.R. Madaah Hosseini *

Department of Materials Science and Engineering, Sharif University of Technology, Azadi Ave., P.O. Box 11155-9466, Tehran, Iran

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ABSTRACT

Finemet soft magnetic alloy has been in the focus of interest in the last years due to its high saturation magnetization, high permeability and low core loss. The great quantity of papers has been devoted to the study of its structural and magnetic properties, confirms this claim. This paper reviews the different researches performed on Finemet up to now. The criteria that should be satisfied in order to have the high glass forming ability in an alloy and also the techniques applied for production of Finemet ribbons, powders and bulk samples have been explained. In addition, the mechanism of devitrification, nanocrystallization and magnetic softness in this applicable magnetic alloy has been discussed in detail. Finally, the effect of different elements substituted with the main constituents in Finemet has been summarized through the studies on the characterization and magnetic properties of different Finemet-type alloys.

1. Introduction

Recently, nanocrystalline soft magnetic alloys have been in the focus of interest due to the superior magnetic properties than their amorphous and crystalline counterparts. Silicon oriented steels were undoubtedly the most important soft magnetic material over the last decades. These steels are used in the numerous core-laminated products ranging from small clock motors to the large power distribution transformers, motors and generators [1,2]. Although the saturation magnetization of the magnetic steels is around 2 T, which is suitable for reducing the size of electrical equipment, their low permeability ($\sim 10^3$) and high core loss (2–10 W kg^{-1}) have caused serious energy concerns. The high amount of core loss in silicon steels is related to the oriented texture and elongated large grains in a specific direction [3]. Historically, the discovery of nanocrystalline soft magnetic alloys has been originated from the improvements performed on the amorphous magnetic alloys to reach the better magnetic properties. Co-based and Fe-based amorphous alloys have been developed as soft magnets. Although the magnetocrystalline anisotropy and thus, the coercivity of these alloys are drastically decreased by amorphization, their low saturation magnetization restricts the applications in many devices [4]. In contrast, Fe-based nanocrystalline alloys have drawn attention due to their high permeability (($\sim 10^5$), high saturation flux density ($\sim$1.5 T) and low core loss (0.1–0.2 W kg^{-1}) [3]. Nanocrystalline Fe–Si–B–Nb–Cu magnetic alloys have been patented under the trade name Finemet. More than 25 years has passed since Yushizawa and his coworkers developed this soft magnetic alloy in 1988 [5]. However, the studies on Finemet in order to improve the structural and magnetic properties have drastically increased in the recent years. Fig. 1 illustrates the growth of researches including journal papers, patents and conference proceedings have been published on the Finemet and FeSiBNbCu magnetic alloys up to now.

Fig. 2 shows the situation of Finemet among soft magnetic alloys. It could be easily seen that Finemet has the highest combination of permeability and saturation flux density among the soft magnetic alloys such as Si-steels, Fe-based and Co-based amorphous alloys, permalloys and ferrites. Since coercivity is inversely proportional with permeability, it could be noted that Finemet has the best soft magnetic properties which outstands it among other alloys.

Finemet with composition of $Fe_{73.5}Si_{13.5}B_9Nb_3Cu_1$ is obtained by heat treating the amorphous melt-spun ribbons which is produced by melt spinning technique. During heat treatment α-Fe(Si)

* Corresponding author.
E-mail address: madaah@sharif.ir (H.R.M. Hosseini).

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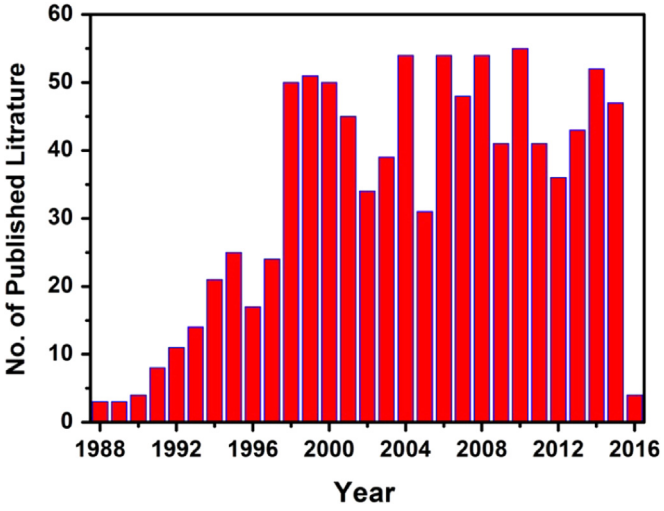

Fig. 1. Number of published literature about Finemet per year [6].

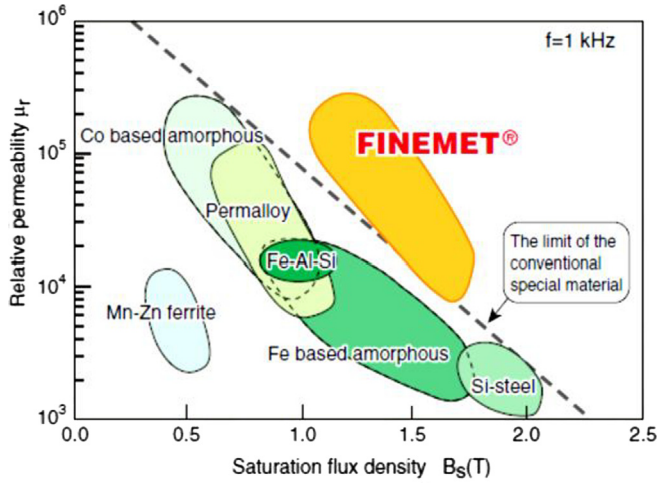

Fig. 2. The relationship between permeability and saturation flux density in several soft magnetic alloys [7].

nanocrystallites with a $D0_3$ structure form in the amorphous matrix [8].

Up to now, many investigations have been done to improve the glass forming ability, the response to the annealing process and consequently, to obtain the better soft magnetic properties. To this end, a wide variety of elements has been added or substituted for the major elements in Finemet. In addition, many studies have been conducted to explore the mechanisms of nano-crystallization and also to make the consolidated bulk alloy.

This review is intended to summarize the recent developments performed on the synthesis, the glass forming ability enhancement, structural characterization, the soft magnetic properties improvement via addition of alloying elements and also the bulk Finemet samples production.

2. Glass forming ability

The term glass forming ability (GFA) is related to the ease or difficulty that a metallic glass (amorphous structure) could be formed. In the most usual method of amorphization, melt spinning process, the high cooling rate in the order of 10^6 K s^{-1} should be applied to form an undercooled liquid or a metallic glass. From thermodynamic point of view, the state of an undercooled liquid corresponds to the non-equilibrium metastable phase [9–11]. Giving sufficient time, depending on the crystallization temperature, results in the crystallization and formation the stable crystalline phases [12].

Before explaining the required conditions for getting high GFA, two parameters should be clearly defined: the reduced glass transition temperature, $T_{rg}=T_g/T_l$, and the supercooled liquid region, $\Delta T_{xg}=T_x-T_g$ where T_g, T_l and T_x are glass transition temperature, liquidus temperature and crystallization temperature, respectively. Between these parameters, T_{rg} is more precisely correlates to the high GFA of glass forming systems. It has been shown that T_{rg} of systems with high GFA is in the range of either 0.66–0.69 [13,14] or 0.6–0.7 [15,16].

Actually, glass transition temperature is defined as either a temperature under which the liquid like structure freezes or a temperature below which the relaxing of the glass takes too long time to be reached. Above T_g the resistance of metallic glasses to shear stresses is low enough that they could be shaped with a minimum effort. To predict T_g in the alloy systems that exhibits the glass transition, many empirical rules have been given so far. The most accepted one is called 'two thirds" expressing the relationship between T_g and T_m as $T_g/T_m \approx 2/3$ where T_m is the melting point [12].

According to the classical definition for the order of a phase transformation, the traditional crystallization transformation (solidification) is considered a first-order transformation while the glass transition is regarded a second-order transformation. This nomination is due to the discontinuity of thermodynamic variables such as volume and energy at T_m. At glass transition temperature these parameters are continuous with respect to the temperature but their first derivatives are discontinuous [9].

To determine T_g of a system, the differential scanning calorimetry (DSC) technique is often used. This measurement is possible since the specific heat capacity of a system increases suddenly to its twice value during cooling at T_g [12]. This behavior has been shown in Fig. 3 for both crystal and glass formations. It is obvious that the increase in the specific heat for a crystal occurs at T_m [17].

It has been indicated that any alloying element added to the

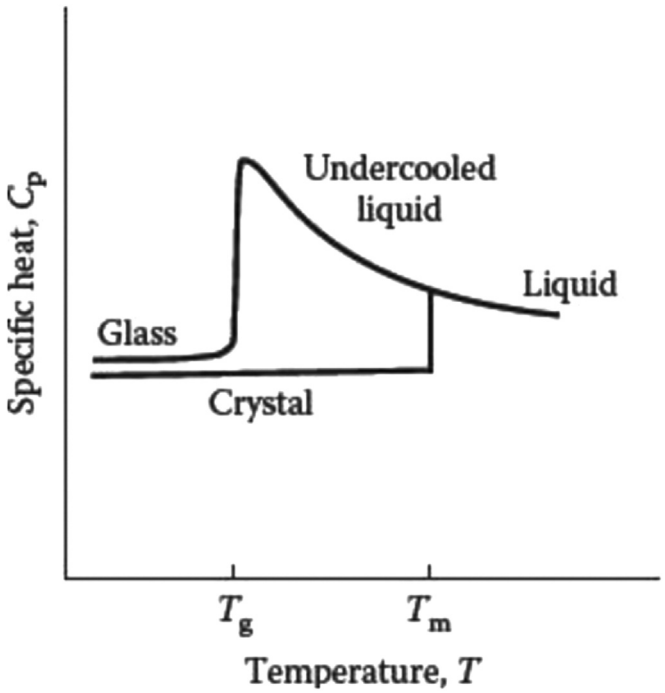

Fig. 3. The change of specific heat as a function of temperature for crystal and glass formations [17].