

Effect of Thermal Condition on Structural Properties of Nano Crystalline $Fe_{73.5}Au_1Nb_3Si_{13.5}B_9$ Alloy

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ABSTRACT

The kinetics of crystallization of different crystalline phases of $Fe_{73.5}Au_1Nb_3Si_{13.5}B_9$ has been studied by differential thermal analysis (DTA). DTA diagrams of amorphous ribbons were taken in nitrogen atmosphere with continuous heating rate of 10 -50°C/min in step of 10°C. The primary exothermic peaks temperature for α -Fe (Si) was found 568°C and the secondary exothermic peak temperature for Fe_2B phase was found 681°C at the same heating rate 20°C/min. Thermal analysis experiment and from the obtained data the activation energy is found 2.50eV. For primary crystallization product, α -Fe(Si) phase of the ribbon and nanocrystalline state was evaluated by XRD. The alloy has been annealed in a controlled way in the temperature range of 450°C to 800°C for 30 minutes. By XRD experiment crystallization onset temperature for α -Fe(Si) phase was found around 650°C. The lattice parameter, the Si content in bcc nanograins and the grain size of bcc grains can easily be calculated from the fundamental peaks of (110) reflection. In the optimized annealing condition the grain size has been obtained in the range 13-25 nm. The lattice parameter and Si at % shows an inverse relationship indicating that silicon diffuses out of α -Fe(Si) grain for which the size α -Fe(Si) lattice is regained. The Curie temperature was found 667°K.

KEYWORDS: DTA, XRD, VSM, Activation energy, Grain size and Curie Temperature.

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I. INTRODUCTION

Amorphous alloys provide an extremely convenient-precursor material for preparation of nanocrystals through the crystallization process controlled by thermal treatments [1-6]. In 1988 Yoshizawa, Oguma and Yamauchi at Hitachi metals Ltd developed the first nanocrystalline ultra soft magnetic alloy called FINEMET having composition $Fe_{73.5}Nb_3Cu_1Si_{13.5}B_9$ from the Fe-Si-B amorphous alloys to which addition of Cu and Nb were added [7]. The Cu and Nb additives play a key role in the formation of the nanocrystalline state Cu by multiplying the nucleation centres and Nb by inhibition the grain growth [2]. The nanocrystalline structures which substantially improve the magnetic properties of Fe-Cu-Nb-Si-B or Fe-Zr-B types alloys is presently attracting much interest [8-9]. In this structures the particle diameter is less than 20 nm and the crystallization from the amorphous phase produces the fine structure of a bcc iron based solid solution. The annealing parameters (time, temperature and atmosphere) must be controlled and the nanocrystalline state can be obtained after conventional annealing under vacuum or atmosphere for typically 1h at >550°C. The FINEMET consists of a two phases microstructure in its optimally annealed condition. The microstructure is made up of a ferromagnetic bcc α -Fe (Si) phase and /or Do_3 type of ordered Fe (Si) phase with grain size of 10-15nm embedded in this residual ferromagnetic amorphous matrix of about 1-2nm thickness. These represent a new family of excellent soft magnetic core materials and have stimulated an enormous research activity due to their potential applications [10-11]. Müller *et. al.* [12] studied the influence of Cu/Nb content and annealing condition on the microstructure and the magnetic properties of FINEMET alloys. Grain size, phase composition and transition temperature were observed to depend on the Cu/Nb content. This paper focuses on the experimental investigation of crystallization behaviour, nanocrystalline structure formation and magnetic properties of $Fe_{73.5}Au_1Nb_3Si_{13.5}B_9$ alloys in the amorphous and annealed states.

II. MATERIALS AND METHODS

Amorphous ribbons with the nominal composition Fe_{73.5}Au₁Nb₃Si_{13.5}B₉ were prepared in an arc furnace on a water-cooled copper hearth under an atmosphere of pure Ar. The purity and origin of the constituent elements were Fe (99.9%), Au (99.9%), Nb(99.9%),Si (99.9%) and B (99.9%) as obtained from Johnson Mathey (Alfa Aesar Inc.). Before melting, the furnace chamber was evacuated (10⁻⁴torr), and flashed with Ar gas. The process was repeated several times to get rid of residual air and finally the furnace chamber were kept in an Ar atmosphere. The mother alloys, which are formed in the form of buttons in a furnace by sudden cooling and then cut into small pieces and is introduced in the quartz tube.

Melt spinning is a widely used production method for rapidly solidifying materials as well as preparing amorphous metallic ribbon [13-14]. In order to prepare amorphous of Fe_{73.5}Au₁Nb₃Si_{13.5}B₉ alloys, the melt spinning facilities was used at the Centre for Materials Science, National University of Hanoi, Vietnam. The resulting ribbon samples had thickness of about 20-25 μm and width ~6 mm. The Factors that is used to Control the thickness of ribbons when angular velocity ω = 2000rev/min and Surface velocity V = 20 m/s to 30 m/s. Gap between nozzle and rotating copper drum (h) = 200 to 30 μm. Oscillations of the rotating copper drum both static and dynamic has maximum displacement 1.5 to 5 μm. Pressure = 0.2 to 3.0 bar at argon atmosphere. Temperature of molten metals T_m ≈ 1500⁰C; the temperature did not exceed 1800⁰ C otherwise quartz tube would be melted. A steady flow of the molten metals on the surface of the rotating drum needs to be ensured. The activation energy was calculated From Kissinger's equation $E = -kT_p \ln \frac{\beta}{T_x^2}$, here E is the activation energy, β is heating rate and the respective crystallization temperature (T_x²). From the obtained data of XRD the lattice parameter has been calculated using equation, $2d \sin \theta = \lambda$ and, $a_0 = d\sqrt{2}$, where λ = 1.54178 Å for Cu – K_α radiation and a₀ is the determined lattice parameter within an error estimated to be ± 0.0001 Å.

Grain size is determined using the following formula, $D_g = \frac{0.9\lambda}{\beta \cos \theta}$, β = FWHM (full width at half maximum) of the peak in radian Si-contents for the nanograins develop during the isothermal annealing at various temperatures have been calculated using the equation is $X = \frac{(a_0 - 2.8812)}{0.0022}$ Where X is at. % Si in the nanograins. Temperature dependent magnetization were performed by VSM.

III. RESULT AND DISCUSSION

DTA traces of as-cast nanocrystalline amorphous ribbon Fe_{73.5}Au₁Nb₃Si_{13.5}B₉ alloy taken in the Nitrogen atmosphere with the heating rates of 10⁰C - 50⁰C/minute at the step of 10⁰C with continuous heating from room temperature to 800⁰C, are presented in figure 1(a) to figure 1(e) respectively. Two well defined exothermic peaks typical for two steps of crystallization processes are manifested from the DTA traces. The first one corresponds to the crystallization of α-Fe(Si) phase and the second one is related to the crystallization of Fe₂B. The onset of crystallization temperatures T_{x1} and T_{x2} have been estimated from DTA traces.

From figure 1.(f) represents a combination of all DTA traces of amorphous ribbon alloy and it is observed that the crystallization of each phase has occurred over a wide range temperature and that the peak temperatures shifted to higher values with the increase of heating rate. That means it requires more that energy for the formation of crystalline phases with increasing heating rates. Table1 crystallization peak temperatures of two phases (T_{p1} and T_{p2}) and crystallization starting temperatures of two phases (T_{x1} and T_{x2}) are given for different heating rates.

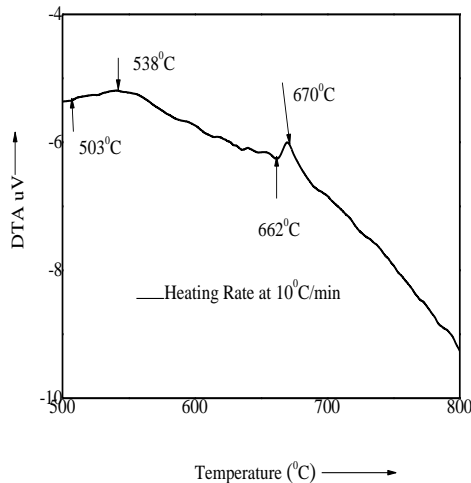


Figure 1(a)

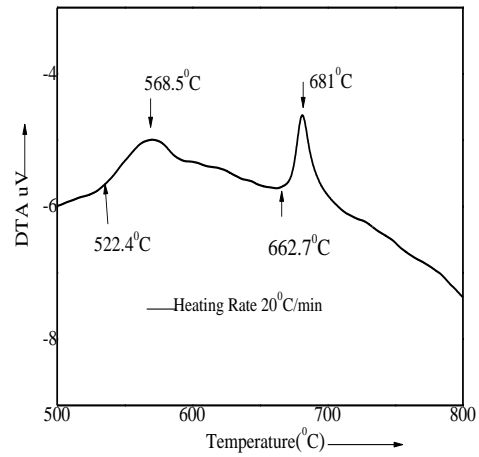


Figure 1(b)

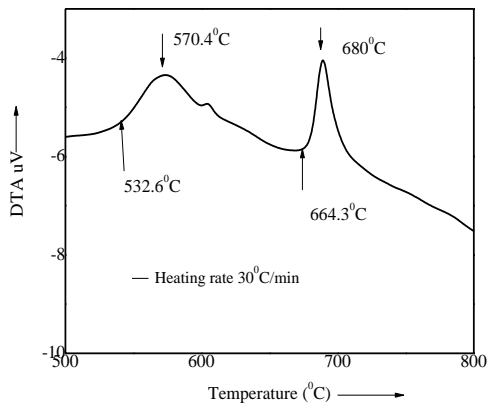


Figure 1(c)

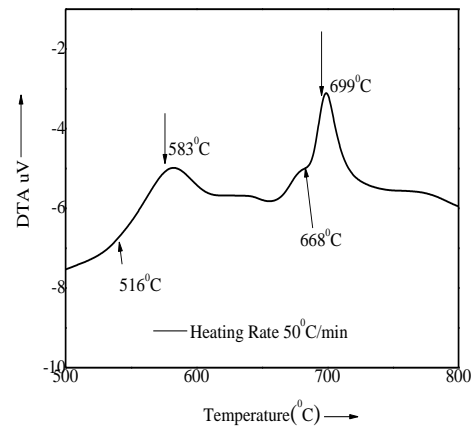


Figure 1(d)

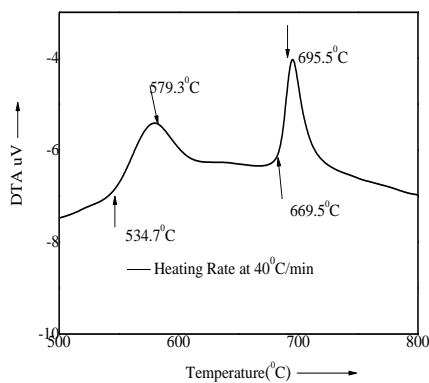


Figure 1(e)

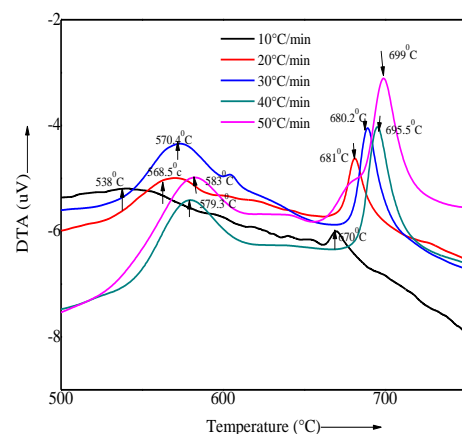
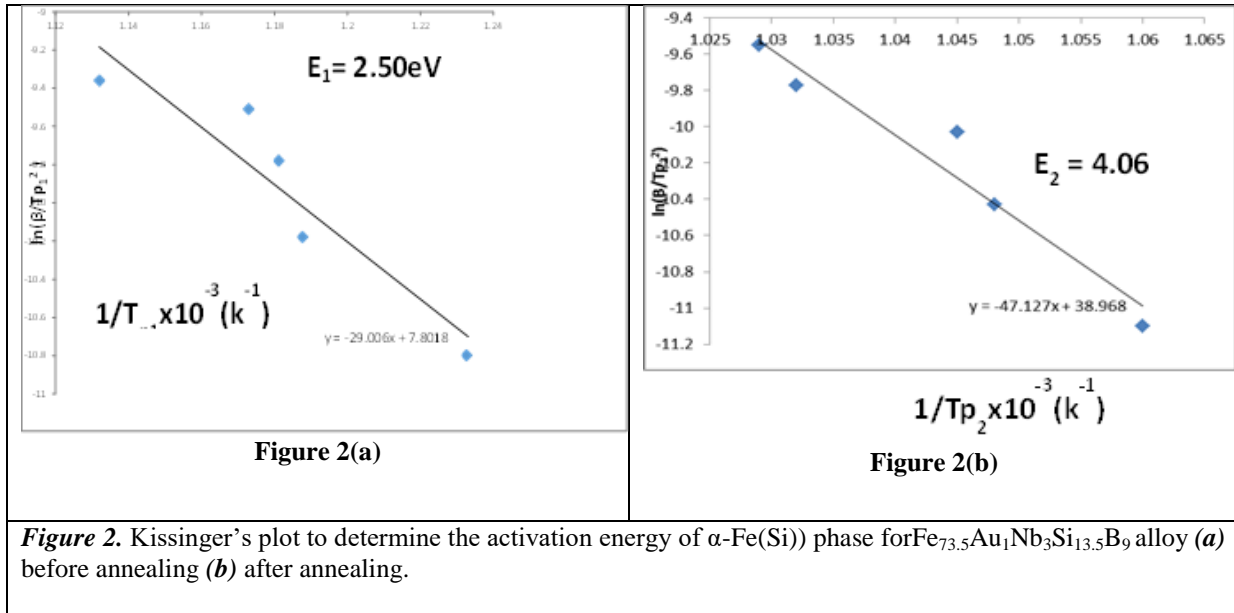


Figure 1(f) Effects of heating rate on DTA traces of nanocrystalline amorphous ribbon with composition $Fe_{73.5}Au_1Nb_3Si_{13.5}B_9$ at the heating rate of $10^\circ C$ to $50^\circ C$ /min

Figure 1. DTA trace of as cast amorphous ribbon $Fe_{73.5}Au_1Nb_3Si_{13.5}B_9$ at the heating rate of (a) $10^\circ C$ /min (b) $20^\circ C$ /min (c) $30^\circ C$ /min (d) $40^\circ C$ /min (e) $50^\circ C$ /min



It has been observed that the crystallization temperature range of first phase occurred within 31.8°C to 67°C. But this range for second crystallization phase is 8°C to 31°C. It is also observed that the peak temperature shift to higher values and crystallization temperature range increase with the heating rates. From figure 1(a) to 1(e) it is seen that two crystallization phenomena have taken place within a temperature gap of around with in 112°C to 133°C. This temperature gap is smaller than the Cu replace Au substituted counterpart. The activation energy of T_{x1} [α -Fe (Si)] and T_{x2} [Fe_2B] phases have been calculated from Kissinger's plot shown in figure 2. It shows that first thermal crystallization activation energy of α -Fe(Si) phase E_1 is 2.5 eV and second Fe_2B phase E_2 is 4.06 eV.

Table 1. The values of crystallization onset temperature, peak temperature with respect to heating rate and activation energy of the nanocrystalline amorphous ribbon with composition $Fe_{73.5}Au_1Nb_3Si_{13.5}B_9$

Heating rate $\beta^\circ C/min$	Onset temperature $T_{x1}^\circ C$	1 st temperature $T_{p1}^\circ C$	Peak range of 1 st state in $^\circ C$	Temperature range of 1 st state in $^\circ C$	Activation energy of the peak before annealing (eV)	Activation energy of the peak after annealing (eV)
10	503	538		35		
20	522.4	568.5		41.1		
30	532.6	570.4		31.8		
40	534.7	579.3		44.6	2.50	4.06
50	516	583		67		

XRD

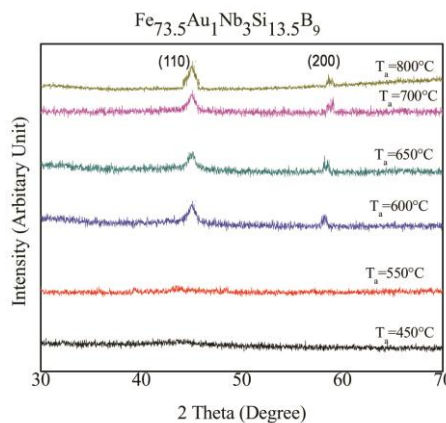


Figure 3. XRD spectra of $Fe_{73.5}Au_1Nb_3Si_{13.5}B_9$ alloys of annealed at different temperatures at constant annealing time 30 minutes

Figure 3 shows typical XRD patterns of bcc α -Fe(Si) phase for the sample of composition Fe_{73.5}Au₁Nb₃Si_{13.5}B₉ after heat treatment 30 minutes at different temperature. From 450°C to 800°C pattern of annealing temperature (T_a) 450°C to 600°C indicates the amorphous nature. After heat treatment at $T_a = 650^\circ\text{C}$ initiation of crystallization takes place. The same patterns were observed for all samples at different annealing temperature indicating the α -Fe(Si) phase are developed on amorphous ribbon after heat treatment.

Moreover, the α -Fe phase is unique crystalline of the alloys annealed at 650°C to 800°C, the variation of intensity of the diffraction lines in patterns obtained under the same condition, reveals that the peak of α -Fe phase in the alloys is increased with increase of the annealing temperature of crystalline nanograin of α -Fe (Si) phase. All the results of θ , d-value, FWHM, a_0 , D_g and at.% Si at different annealing temperature of these composition are listed in Table 2. In figure 4 the lattice parameter of α -Fe(Si) grains embedded in the amorphous matrix of various annealed samples in the temperature range between 650°C to 800°C has been performed, with the increase of annealing temperature lattice parameter slightly decreases. These results agree with the lattice parameter of α -Fe(Si) phase is always smaller than that of pure Fe. The Si-content of the alloy Fe_{73.5}Au₁Nb₃Si_{13.5}B₉ at 650°C to 800°C at constant annealing time 30 minutes are found to be in the range of 9.01% to 12.36%. All these results are presented in Table 2 and the pattern of change in Si content with respect to annealing temperature are presented in figure 4. Above or below this critical annealing temperature at.%Si decreases as lattice parameter increases. Figure 5 the mean grain size of the nanograins determined from the X-ray fundamental line (110) using the Scherrer formula are presented. The increasing of annealing temperature initiates partitioning of Si in the α -Fe(Si) phase. In the range of annealing temperature 650°C to 800°C, the grain size remains in the range 13 -25nm.

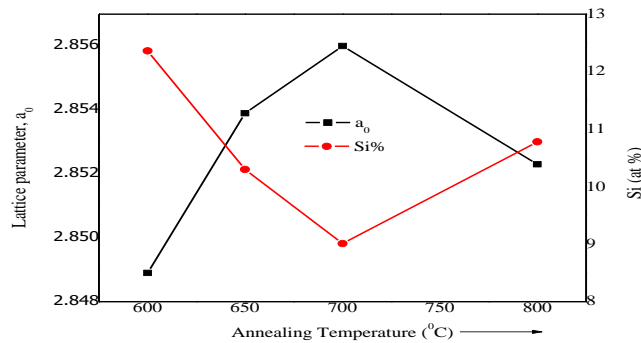


Figure 4. Change of Si (at. %) content and Lattice Parameter with different annealing temperature for the sample with composition Fe_{73.5}Au₁Nb₃Si_{13.5}

These facts reveal that heat treatment temperature should be limited with 650°C to 700°C to obtained soft magnetic behavior which will be clear that nearly constant grain size.

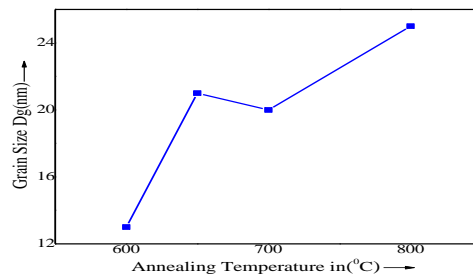


Figure 5. Change of Grain Size with different annealing temperature for the sample with composition Fe_{73.5}Au₁Nb₃Si_{13.5}B₉

Table 2. Experimental XRD data of nanocrystalline $Fe_{73.5}Au_1Nb_3Si_{13.5}B_9$ amorphous ribbon at different annealing temperatures

Annealing in °C	Temp.	θ (deg.)	d (Å)	FWHM (deg.)	a_0 (Å)	D_g (nm)	Si (at. %)
450	--	--	--	--	--	--	--
550	--	--	--	--	--	--	--
600	--	--	--	--	--	--	--
650	22.48	2.0145	0.65	2.8489	13	12.36	
700	22.46	2.0176	0.40	2.8533	21	10.30	
750	22.44	2.0195	0.44	2.8560	20	09.01	
800	22.45	2.0169	0.325	2.8523	25	10.78	

Temperature Dependence of specific Magnetization:

The variation of saturation magnetization (M_s) as a function of temperature in the range 300 k to 800 k measured with an applied field of 10kOe in the amorphous state for the nanocrystalline amorphous samples with composition $Fe_{73.5}Au_1Nb_3Si_{13.5}B_9$ are shown in figure 7.

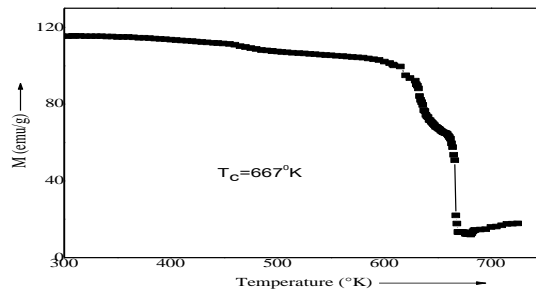


Figure 7 (a) Temperature dependence of specific magnetization of amorphous nanocrystalline ribbons with composition $Fe_{73.5}Au_1Nb_3Si_{13.5}B_9$ alloy

From these curve T_c has been determined as the temperature corresponding to the inflexion point where the rate change of magnetization with respect to temperature is maximum shown in figure 7(a) and 7(b). As the temperature approaches to the T_c , magnetization falls more rapidly near to zero as the thermal energy exceeds the magnetic ordering or the exchange energy.

The accurate determination of T_c of amorphous material is really difficult due to irreversible components of the structural relaxation like long range internal stress, topological and chemical short range order.

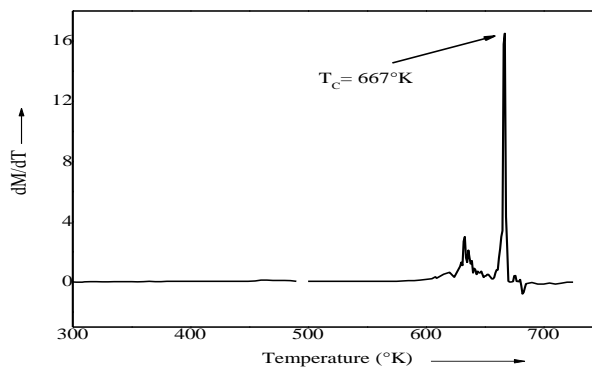


Figure 7(b) $\frac{dM}{dT}$ versus temperature curve of amorphous Nanocrystalline ribbons with composition $Fe_{73.5}Au_1Nb_3Si_{13.5}B_9$ alloy.

IV. CONCLUSION

The crystallization behavior of the sample was investigated by the experiments of DTA and XRD and VSM as a result the following outlined can be concluded:

- DTA experiment was performed for five different rates 10 to 50°C/min in steps of 10⁰C/min up to a temperature of 800°C. DTA reveals the primary and secondary crystallization onset temperature with the manifestation of two well defined exothermic peaks corresponding to nanocrystallization α -Fe(Si) (T_{x_1}) and Fe₂B(T_{x_2}) phases respectively. First crystallization phase T_{x_1} indicates stability of amorphous state of structural stability and magnetic ordering values of T_{x_1} are observed 522.4°C for Fe_{73.5}Au₁Nb₃Si_{13.5}B₉ with heating rate 20°C/min.
 - The activation energy of the first crystallization phase α -Fe(Si) and second crystallization phase Fe₂B phase before and after annealing is found 2.50eV and 4.5eV respectively.
 - The amorphous stage of the as-cast ribbon has been confirmed by XRD. The evolution of the primary phase on annealed samples has been confirmed as α -Fe(Si) phase with average grain grown in the amorphous matrix 13 - 30 nm for Fe_{73.5}Au₁Nb₃Si_{13.5}B₉. This is quite reasonable since their crystallization onset temperature is 650°C and higher. The lattice parameter and Si at% shows an inverse relationship indicating that Si diffuses out of α -Fe(Si) grain for which the size of α -Fe lattice is regained.
 - The Curie temperature of the sample has been determined by temperature dependence saturation magnetization that is 394°C. The sharp fall of M_s at T_c indicates that the material is quite homogeneous.
- Finally**, concluded that promising initial results on FINEMET alloy suggest Cu replace Ag that that might also find their way in high temperature soft magnetic applications. The playground of microstructural engineering of soft magnetic properties will undoubtedly after new discoveries for future materials scientist and engineers.

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