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Article

The Effect of High Temperature Annealing on Magnetic and Structural properties of Mn-Fe-P-Si-based Glass-Coated Microwires

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Abstract: In this paper, the impact of annealing at different temperatures (973 K, 1073 K and 1123 K for 1h) on the magnetic and microstructural properties of Mn-Fe-P-Si based glass-coated microwires is studied. Annealing significantly influences the magnetic and microstructural properties of Mn-Fe-P-Si glass-coated microwires. XRD analysis reveals that increasing the annealing temperature leads to a notable increase in the Fe₂P phase content, reaching a maximum at 1123 K, while simultaneously reducing the presence of secondary phases observed in the as-prepared sample. The reduction of secondary phases in Mn-Fe-P-Si -based microwires has a profound impact on their magnetic behavior. High coercivity values are observed in both the as-prepared and annealed samples. However, annealing at higher temperatures (1073 K and 1123 K) results in a significant reduction in coercivity, decreasing from 1200 Oe for the sample annealed at 973 K to 300 Oe and 150 Oe, respectively. In addition, the sample annealed at 1123 K for 1h shows a notable paramagnetic behavior for loops measured from 200 K to 300 K. Meanwhile, the other samples show ferromagnetic behavior for all measuring temperature from 5 to 300 K. This study highlights the significant potential for tailoring and modifying various magnetic properties of Mn-Fe-P-Si glass-coated microwires, including metamagnetic phase transitions, magnetic behavior, and the control of magnetic response (hardness/softness). Such tailored properties make Mn-Fe-P-Si -glass-coated microwires promising candidates for a wide range of applications.

Keywords: Mn-Fe-P-Si alloys; glass-coated microwires; Taylor–Ulitsky Technique; annealing; XRD analysis

1. Introduction

In recent years, the continuous development of magnetic micro & nanostructures has significantly advanced both fundamental scientific research and technological applications [1–5]. Unlike bulk magnetic materials, the systematic engineering of micro & nanomaterials has led to groundbreaking advances in areas such as the fabrication of magnetic micro & nano structures with tailorable physical properties, the exploration of multidimensional magnetic properties in magnetic micro & nanostructures, and their prospective applications [3–5]. In addition, precise control over the grain size, morphology, and phase content of magnetic micro & nanostructures is of paramount in determining their unique physical and chemical properties, which are essential for potential applications [6,7].

In particular, micro- and nanostructured magnetic materials that can undergo thermoelastic martensitic phase transitions (TMPTs) have emerged an attractive area of research due to their remarkable features [8–31]. These materials have a distinctive synergy of functions, presenting great opportunities for technological advancement. Prominent features encompass shape memory (SM), giant superelasticity (GS), magnetic field-induced strain (MFIS), and elastocaloric and magnetocaloric (EMC) effects [2,4,5,8–34].

In recent decades, there has been a surge of research dedicated to magnetocaloric materials, which serve as essential components in magnetic refrigeration systems [2,4,5,11]. Despite their potential, existing refrigerators often operate at relatively low frequencies (up to a few Hz), hindering their overall cooling efficiency [35,36]. Theoretical investigations have indicated that the cooling efficiency of magnetic refrigerators can be significantly enhanced by optimizing the shape of the magnetocaloric materials employed [37–39]. Specifically, it has been theorized that a magnetic materials composed of magnetocaloric microwires, such as Gd and NiMnGa wires, offers an optimal device configuration compared to powder or laminate structures [37–39]. The increased surface-to-volume ratio of magnetocaloric wires is expected to facilitate more efficient heat transfer between the magnetic refrigerant and the surrounding liquid.

Mn–Fe–P–Si alloys have emerged as promising magnetocaloric materials due to their substantial magnetocaloric effect near room temperature [40,41]. The low cost of these materials, which do not require expensive or critical elements, further enhances their appeal as viable candidates for large-scale cooling applications. MnFePSi alloys exhibit a hexagonal Fe₂P-type crystal structure (space group P6₂m) [42]. Within this structure, Mn and Fe atoms occupy specific sites: Mn atoms occupy pyramid-shaped sites (3g), while Fe atoms favor tetrahedral sites (3f) [42,43]. Neutron diffraction studies have elucidated the ferromagnetic (FM) state in these alloys, revealing the in-plane alignment of both Mn and Fe magnetic moments within the basal ab plane [43]. Density Functional Theory (DFT) simulations have further highlighted the unique mixed magnetism of Mn–Fe–P–Si, with Mn atoms maintaining a relatively constant magnetic ordering even above the critical temperature (T_c), while Fe atoms exhibit a significant increase in magnetic moment at T_c . The presence of Phosphorus (P) and Silicon (Si) atoms is crucial in enabling Fe atoms to develop a strong magnetic moment within Mn–Fe–P–Si alloys [43]. This combination of properties makes Mn–Fe–P–Si alloys highly promising for applications such as enhancing the efficiency of solid-state cooling systems and magnetic refrigeration technologies [44–49]. From a materials engineering perspective, achieving a high fraction of the desirable Fe₂P phase in Mn–Fe–P–Si alloys presents a significant challenge. Previous research has demonstrated that conventional methods often require prolonged heat treatment, spanning several days or months, at elevated temperatures to form a substantial volume fraction of the Fe₂P phase and ensure compositional homogeneity within Mn–Fe–P–Si materials [50–54]. Consequently, these production methods can lead to increased overall costs. The ongoing miniaturization trend in modern technology has extended to the field of magnetocaloric devices, further emphasizing the appeal of Mn–Fe–P–Si alloys [44–49,55–66]. A distinctive characteristic of Mn–Fe–P–Si lies in its versatility, allowing for its fabrication into various micro-scale structures, including particles, wires, ribbons, films, and complex layered configurations. The primary magnetic parameters of Mn–Fe–P–Si alloys, such as coercivity, thermomagnetic behavior, magnetic transitions, and Curie temperature, are significantly influenced by factors like chemical composition, annealing conditions, secondary phases, and fabrication techniques. Consequently, a wide range of Curie temperatures, spanning from 100 K to 470 K, has been reported [19,44–49,55–67]. This remarkable shape versatility of MnFePSi alloys translates into a plethora of potential applications [44–49,55–67].

Recently, we succeeded to fabricate Mn–Fe–P–Si microwires with Fe₂P as the main phase. Interesting magnetic behavior, such as metastable magnetic phase transition, high coercivity, multistep magnetic behavior and interesting thermomagnetic curves with different magnetic field and temperature have been reported, which does not exist in the master bulk alloy [19,55,67].

Glass-coated microwires, particularly those with sub-micrometric diameters, have garnered significant attention due to their diverse applications, especially in the field of sensing technology

[68,69]. These composite materials consist of a metallic nucleus coated by a thin, insulating glass shell. This unique structure offers several advantages. Compared to bulk or thin film forms Mn-Fe-P-Si microwires enable novel applications across various industrial sectors [68,69]. The glass coating provides mechanical and anti-corrosion protection for the metallic nucleus, preventing electrical short circuits and enhancing corrosion resistance, thereby extending the microwire's lifespan. Moreover, the thickness of the glass coating can be precisely controlled during the manufacturing process to meet specific application requirements.

The current study presents a comprehensive investigation of the structural and magnetic properties of Mn-Fe-P-Si glass-coated microwires. Notably, the influence of annealing conditions on the magneto-structural properties was explored, revealing significant differences in the physical properties of Mn-Fe-P-Si-based glass-coated microwires before and after annealing. Significant variations in magnetic parameters, including coercivity, presence of secondary phases, magnetic stability, thermomagnetic behavior, and microstructure, were observed upon altering annealing conditions. These findings underscore the heightened sensitivity of Mn-Fe-P-Si microwires to annealing compared to their bulk alloy counterparts. This sensitivity opens up promising avenues for tailoring intriguing physical phenomena, such as metamagnetic phase transitions and bi-stable magnetic behavior.

2. Materials and Methods

2.1. Fabrication of Bulk Mn-Fe-P-Si-Master Alloy

This study focuses on the fabrication and studies of thin, Mn-Fe-P-Si alloy glass-coated microwires. The fabrication process can be roughly divided into two main stages: the production of a bulk Mn-Fe-P-Si alloy ingot and the subsequent microwires preparation from this ingot. The first stage involves the meticulous production of a $\text{Mn}_{40}\text{Fe}_{30}\text{P}_{15}\text{Si}_{15}$ bulk alloy via ARC melting. The raw materials employed in the fabrication process consisted of high-purity crystals of manganese (Mn, $\geq 99.5\%$), iron (Fe, $\geq 99.99\%$), iron-phosphorus chunks (FeP, $\geq 98\%$), and silicon (Si, $\geq 99.999\%$). To compensate for potential manganese losses during the arc-melting process, an excess of 5 wt% of manganese was intentionally added to the initial mixture.

The powder mixture is then carefully transferred into a Copper crucible specifically designed for high-temperature applications. The crucible is subsequently placed within a vacuum chamber filled with argon gas and subjected to an electric arc, inducing intense localized heat that melts the powder mixture. To ensure complete liquefaction and homogenization, the melting process is meticulously controlled. Upon complete melting, the electric arc is extinguished, and the molten metal is allowed to cool progressively under controlled atmospheric conditions. This controlled cooling promotes the formation of a uniform and homogenous $\text{Mn}_{40}\text{Fe}_{30}\text{P}_{15}\text{Si}_{15}$ bulk alloy ingot. To further refine the microstructural homogeneity and elevate the overall quality of the bulk alloy, multiple remelting cycles can be implemented. This involves repeating the melting and homogenization stages, typically for 5 cycles. Remelting contributes to refining the grain structure of the bulk alloy. Following solidification, the $\text{Mn}_{40}\text{Fe}_{30}\text{P}_{15}\text{Si}_{15}$ bulk alloy ingot undergoes comprehensive characterization to evaluate its structural and compositional properties. This characterization step is crucial for ensuring the quality and suitability of the bulk alloy for subsequent processing into microwires.

2.2. Preparation of Mn-Fe-P-Si Glass-Coated Microwires

Glass-coated microwires were fabricated using the Taylor-Ulitovsky technique, with a Duran glass coating (Figure 1(b-d)). For further details regarding the fabrication process and experimental conditions, please refer to previous studies [19,55,67–73]. The microwires produced have a total diameter (D) of 28 μm and a metallic nucleus diameter (d) of 14.7 μm . EDX analysis confirmed a chemical composition of $\text{Mn}_{40}\text{Fe}_{30}\text{P}_{15}\text{Si}_{15}$ with a deviation of approximately 0.5% from the nominal stoichiometry. This deviation can be attributed to manganese evaporation during the ingot melting

and subsequent microwire preparation processes (casting and drawing). The as-prepared glass-coated microwires were encapsulated between two ceramic plates and subjected to annealing at 973 K, 1073 K, and 1123 K for a duration of 1 hour within a vacuum environment (pressure $P = 2 \times 10^{-4}$ Pa). A heating rate of 10 K/min was employed, followed by furnace cooling. To assess the potential influence of annealing temperature on chemical composition, EDX analysis was conducted on the annealed samples.

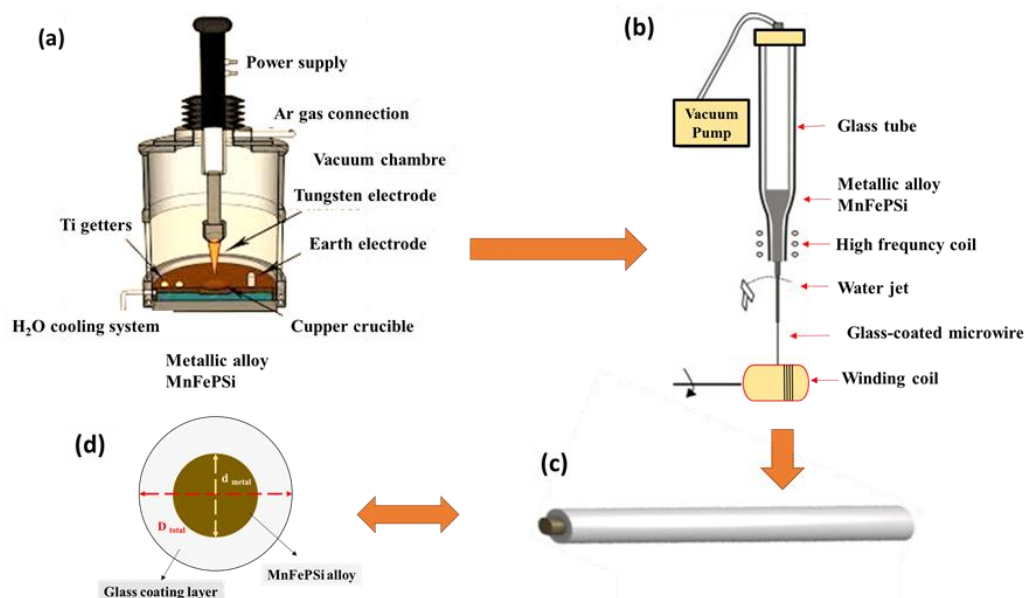


Figure 1. Image of the experimental setup facility for the fabrication of Mn-Fe-P-Si glass-coated microwires. (a) Vacuum ARC melting, (b) Taylor-Ulitovsky method for production of glass-coated microwires, (c) and (d) the Mn-Fe-P-Si-based glass-coated microwires sketch.

2.3. Characterization of the Structural and Magnetic Properties

Structural characterization of the samples was conducted using a Bruker D8 Discovery X-ray diffractometer equipped with $\text{CuK}\alpha$ radiation at room temperature. A θ - 2θ scanning geometry with a step size of 0.02° and a range of 0° to 80° was employed.

Magnetic characterization was performed using a vibrating-sample magnetometer integrated within a Physical Property Measurement System (PPMS). Thermomagnetic characterization involved measuring magnetization as a function of temperature (T) under a constant applied magnetic field. Measurements were conducted at low field values of 50 Oe, aligned with the wire axis, within a temperature range of 5 K to 400 K. A zero-field-cooled (ZFC)-field-cooled (FC)-field-heating (FH) protocol was utilized to acquire the data. Initially, the sample was cooled from 400 K (paramagnetic state) in the absence of a magnetic field. Subsequently, a chosen magnetic field was applied, and magnetization data was collected during heating to 350 K (ZFC curve). Following this, without removing the field, data was collected during cooling (FC curve) and then during heating again (FH curve). A constant heating/cooling rate of 2 K/min was maintained throughout the measurements. Hysteresis loops were measured using a vibrating-sample magnetometer with a maximum applied field of 90 kOe aligned along the microwire axis within the temperature range of 5 K to 300 K. To facilitate comparison of results, all magnetic data were presented in terms of normalized magnetization (M/M_{sat} or $M/M_{5\text{K}}$), where M_{sat} (or $M_{5\text{K}}$) represents the magnetic moment measured at saturation field or at 5 K, respectively. The Curie temperature was determined by identifying the minimum point of the first derivative of the magnetic moment versus temperature curves. It is imperative to note that all characterizations, including magnetic measurements, X-ray diffraction (XRD) analysis, and morphological investigations, were exclusively conducted on the glass-coated microwire samples.

3. Results

3.1. Structure Characterizations

Figure 2 shows the X-ray diffraction (XRD) analysis conducted in as-prepared and annealed at 973 K, 1073 K, and 1123 K for 1 hour Mn-Fe-P-Si glass-coated microwires, reveal notable differences in their microstructural properties. All diffractograms exhibited a broad halo below $2\theta \approx 30^\circ$ (not shown), attributed to the amorphous glass coating, as previously reported [34,67–79]. The as-prepared sample displayed three distinct phases, while annealed samples exhibited two phases. The predominant phase in all samples was Fe_2P with space group P-62m. Secondary phases included hexagonal Mn_5Si_3 (P6₃/mcm) in the as-prepared sample and cubic Fe_3Si (Fm-3m) in both the as-prepared and annealed samples at 973 K. Notably, the absence of the hexagonal Mn_5Si_3 phase in annealed samples at 1073 K and 1123 K for 1 hour, suggests that Mn atoms may occupy Fe sites, leading to an increase in the cubic Fe_3Si phase content. It was observed that annealing promotes an increase in the content of the main Fe_2P phase while reducing the amount of secondary phases in Mn-Fe-P-Si microwires. For the samples annealed at 973 K and 1073 K for 1 hour, an enhancement in the peaks intensities at 2θ values of 30° , 46.9° , 53.5° , and 65.3° was observed, indicating a higher content of the Fe_2P phase. For the sample annealed at 1123 K for 1 hour, only four peaks were observed at $2\theta = 30^\circ$ (200, Fe_2P), $2\theta = 35.1^\circ$ (002, Fe_3Si) and 46.3° (200, Fe_2P), and $2\theta = 53.5^\circ$ (200, Fe_2P). Calculations of the lattice parameter revealed a slight decrease from $a = 0.58 \pm 0.02$ nm for the as-prepared sample to $a = 0.54 \pm 0.02$ nm for the sample annealed at 973 K for 1 hour, followed by a sharp increase to 0.61 ± 0.02 nm for the sample annealed at 1123 K for 1h (Table 1). These variations in microstructure and phase formation significantly influence the magnetic behavior of the annealed samples, as discussed in the following section on magnetic properties analysis. Additionally, an analysis of the average grain size (D_g) revealed a significant variation. D_g increased from 36 nm for the as-prepared sample to 133 nm for the sample annealed at 973 K for 1 hour and then reaching 147 nm for the sample annealed at 1123 K for 1h (Table 1).

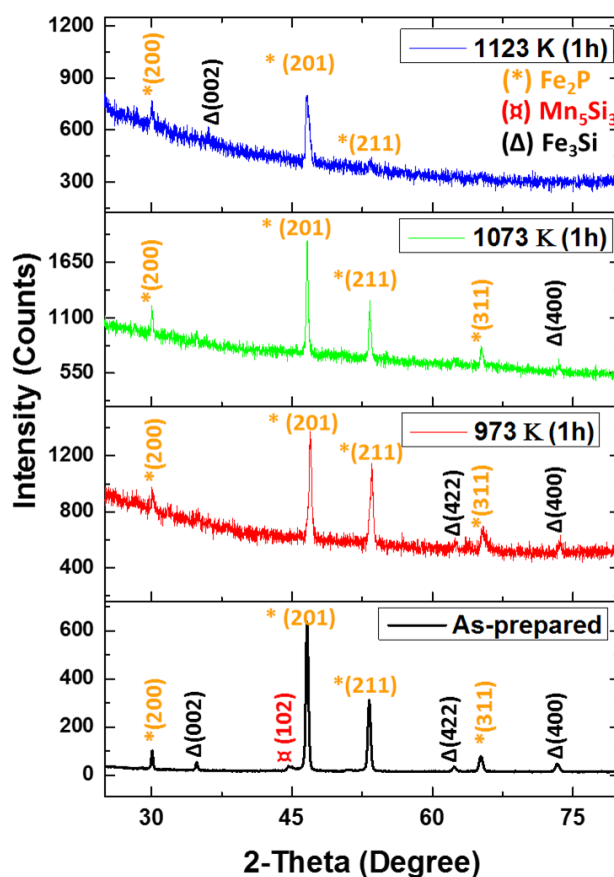


Figure 2. Room temperature X-ray diffraction profile of as prepared and different temperature annealed 973 K, 1073 K and 1123 K for 1h of MnFePSi glass-coated microwires.

Table 1. Chemical composition, lattice constant and the average grain size of as-prepared and different temperature annealing of Mn-Fe-P-Si-based glass-coated microwires.

Samples	Chemical composition	Lattice constant (a) nm	D _g (nm)
As-prepared	Mn ₄₀ Fe ₃₀ P ₁₅ Si ₁₅	0.58	36
973 K (1h)	Mn ₄₀ Fe ₃₀ P ₁₅ Si ₁₅	0.54	136
1073 K (1h)	Mn ₄₀ Fe ₃₀ P ₁₅ Si ₁₅	0.60	141
1123 K (1h)	Mn ₄₀ Fe ₃₀ P ₁₅ Si ₁₅	0.61	148

3.2. Magnetic Hysteresis Loops Characterization

Figure 3 summarizes the magnetic hysteresis loops of Mn-Fe-P-Si-based glass-coated microwire samples measured at 5K. All magnetic measurements were performed in the in-plan configuration with the applied magnetic field aligned parallel to the wire axis, where the easy magnetization axis is expected. For as-prepared sample, a maximum magnetic field of about 90 kOe is used to have the fully saturated sample, while 30 kOe is used for the annealed sample. In addition, all magnetic measurements were performed keeping the glass-coated layer. As seen in Figure 3, notable changes in the magnetic behavior are found between the as-prepared sample and annealed for different temperature samples. Firstly, the as-prepared sample shows unsaturated hysteresis loops even at maximum applied magnetic field, i.e. 90 kOe, while the saturated hysteresis loops are observed in the annealed samples even below 5 kOe. Additionally, the hysteresis loops of as-prepared samples show unusual meta-magnetic transition and multi-step magnetic behavior at low temperature (see Figure 3b). Such unusual magnetic behavior is discussed in detail in our previous works [19,74–76]. For the sample annealed at 1123 K for 1 h, the hysteresis loops show an inclined shape that should be attributed to the micro magnetic structure induced by high temperature annealing process. From Figure 3b, it is evidenced that the sample annealed at 973 for 1 h exhibits hard magnetic behavior compared to the rest of the samples. Meanwhile, magnetic softening is observed in the sample annealed at 1123 K for 1h.

By investigation of Mn-Fe-P-Si glass-coated microwire samples at room temperature, i.e., $T \approx 300$ K, notably different magnetic behavior is seen compared to the samples measured at 5 K. First, the as-prepared samples exhibit regular magnetic behavior without any distortion in the magnetic hysteresis loop. In addition, magnetic softening is evidenced by the hysteresis loops measured at 300 K at low magnetic fields (see Figures 3b and 4b). Secondly, a notable reduction in the saturation field follows from complete saturation at a magnetic field below 5 kOe. The same behavior is seen in the annealed samples, in which the hysteresis loops measured at room temperature exhibit soft magnetic behavior compared to the loops measured at 5K. The softest magnetic behavior is observed in the annealed sample at 1123 K for 1 h. In addition, a strong paramagnetic contribution is seen in the sample annealed at 1123 K, where the hysteresis loop has almost liner shape (see Figure 4b).

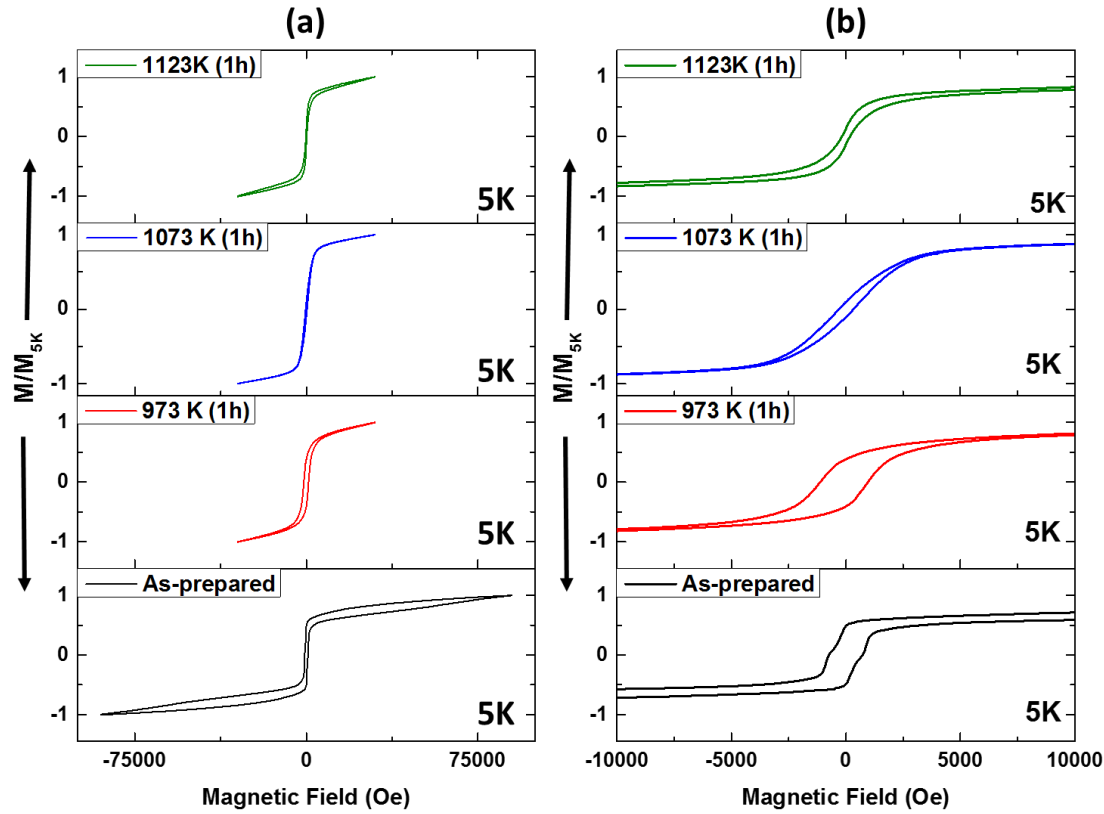


Figure 3. The in-plane hysteresis loops of as-prepared and annealed at 973 K, 1073 K and 1123 K for 1h of Mn-Fe-P-Si glass-coated microwires measured at 5K (a) full measuring scale and (b) low scale.

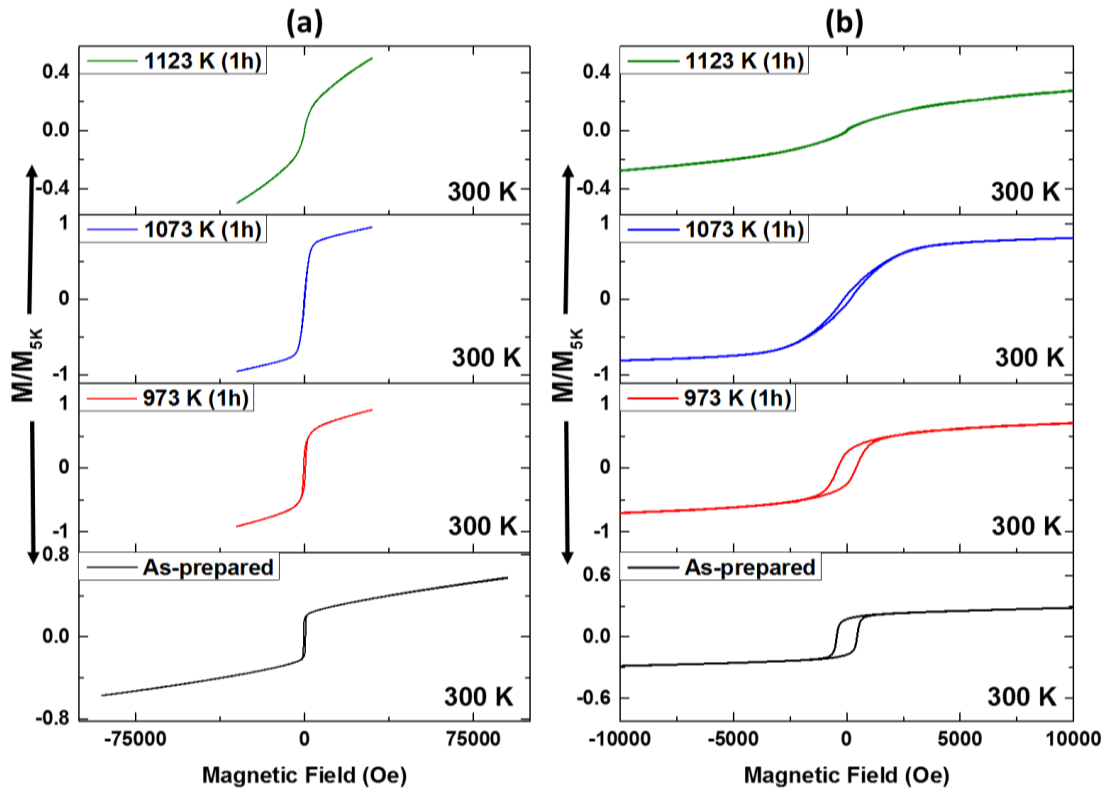


Figure 4. The in-plane hysteresis loops of as-prepared and annealed at 973 K, 1073 K and 1123 K for (1h) of Mn-Fe-P-Si glass-coated microwires measured at 300K (a) full measuring scale and (b) low-field region.

Figure 5 illustrates the temperature dependence of coercivity (H_c) for both as-prepared and annealed Mn-Fe-P-Si glass-coated microwires. In general, the $H_c(T)$ dependencies are typical for ferromagnetic behavior, with H_c increasing as temperature decreases from 300 K to 5 K. The sample annealed at 973 K for 1 hour demonstrated the highest H_c -value compared to the other samples. The maximum H_c value at 5 K is approximately 1200 Oe. For samples annealed at 1073 K and 1123 K, a notable reduction in H_c was observed, decreasing from 325 Oe to 150 Oe and from 175 Oe to 30 Oe, respectively, over the temperature range of 5 K to 300 K. This tunability of magnetic properties of Mn-Fe-P-Si glass-coated microwires by annealing can be attributed to the internal stresses relaxation and the average grain size modification. The main origin of such internal stresses is the difference in thermal expansion coefficients of the glass coating and the metallic alloy [68,69,72]. Such internal stresses relaxation can induce modifications in the microstructure and magnetic properties of the metallic nucleus.

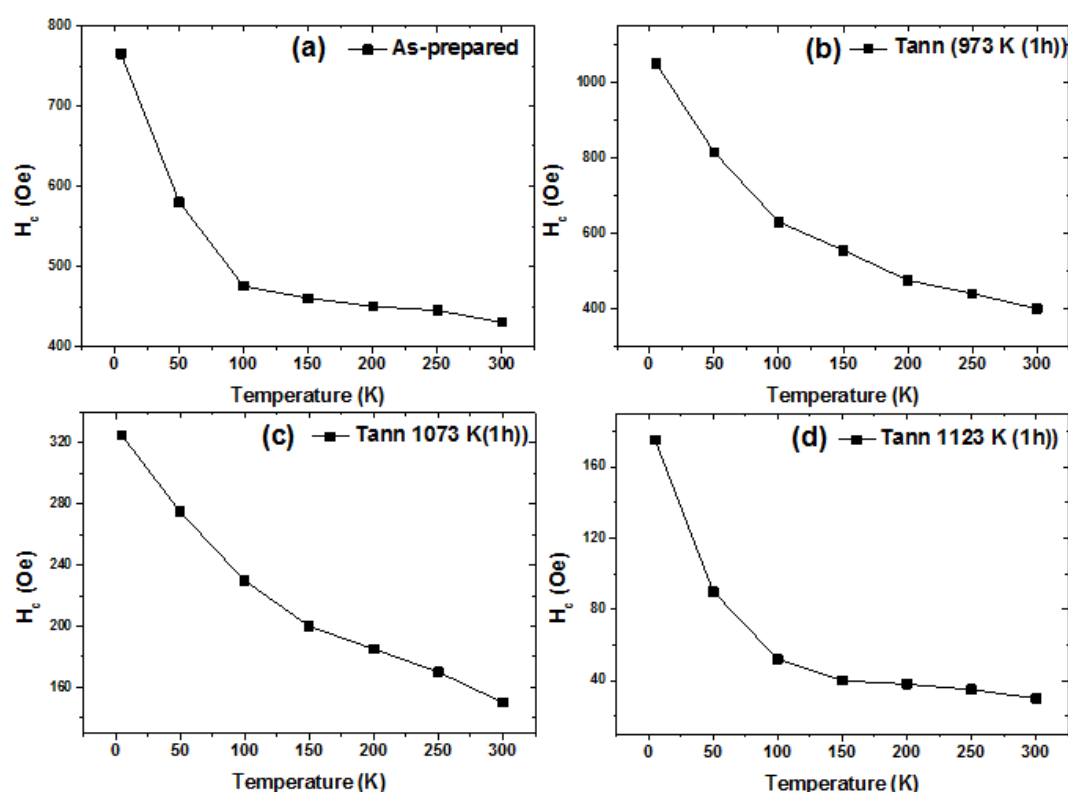


Figure 5. Temperature dependence of coercivity, H_c , in Mn-Fe-P-Si-based glass-coated microwire, (a) as-prepared, (b) annealed at 973 K for 1h, (c) annealed at 1073 K for (1h) and 1123 K for (1h).

On the other hand, it was previously reported that the $H_c(D_g)$ dependence of nanocrystalline materials shows a decrease in H_c for $D_g \geq 100$ nm as $H_c \sim 1/D_g$ [77]. Therefore, the increase in D_g upon annealing should be associated with a decrease in H_c .

For better understanding the magnetic behavior of Mn-Fe-P-Si-based glass-coated microwires, thermomagnetic characterization was conducted by measuring magnetization as a function of temperature (T) under a constant applied magnetic field. The measurements were performed at low magnetic field (1 kOe and 5 kOe) (see Figures 6 and 7), all aligned with the wire axis in the temperature from 5 to 400 K. (FC)-field-heating (FH) protocol was employed to acquire the data. Initially, the sample was cooled down from 400 K in the absence of a magnetic field. Then, a chosen magnetic field was applied, and the magnetization data was collected while heating the sample to 400 K. Subsequently, without removing the field, the data was collected during cooling (FC curve) followed by heating again (FH curve). A constant heating/cooling rate of 2 K/min was maintained throughout the measurements.

The FC curve for as-prepared sample shows different behavior compared to the annealed samples. While FH curve perfectly matches with the FH of annealed samples. More details about the thermomagnetic behavior of the as-prepared sample is discussed in our previous works [19,74]. FC and FH curves for annealed sample at 973 K show regular ferromagnetic behavior where, the magnetization increase monotonically by decreasing the temperature from 400-5 K. For sample annealed at 1073 K the same behavior is seen, but with two different slopes on $M(T)$ dependence: the magnetization rate by decreasing the temperature is changed. This change in the magnetization rate and slopes is due to the existence of secondary phase, as will be discussed in the XRD section. For annealed sample at 1123 K for 1h, notable hysteric behavior is observed, where the separation between FC and FH appears at temperature range from 50-350 K. The hysteretic behavior indicates the common thermomagnetic behavior of the Fe₂P-based alloys. Thus, the annealing affects the thermomagnetic response of Mn-Fe-P-Si-based glass-coated microwires.

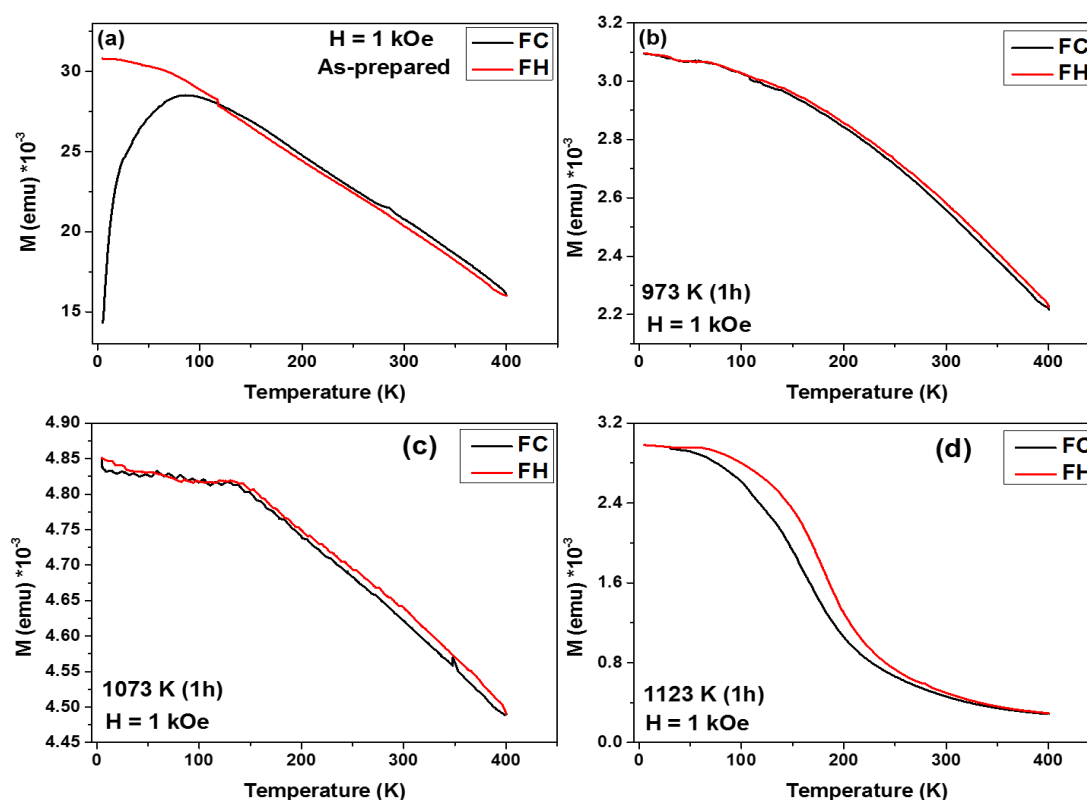


Figure 6. FC and FH temperature dependence of as-prepared (a) and different temperature annealed (b) 973 K (1h), (c) 1073 K (1h) and (d) 1123 K (1h) of Mn-Fe-P-Si-based glass-coated microwire measured at magnetic field ($H = 1$ kOe).

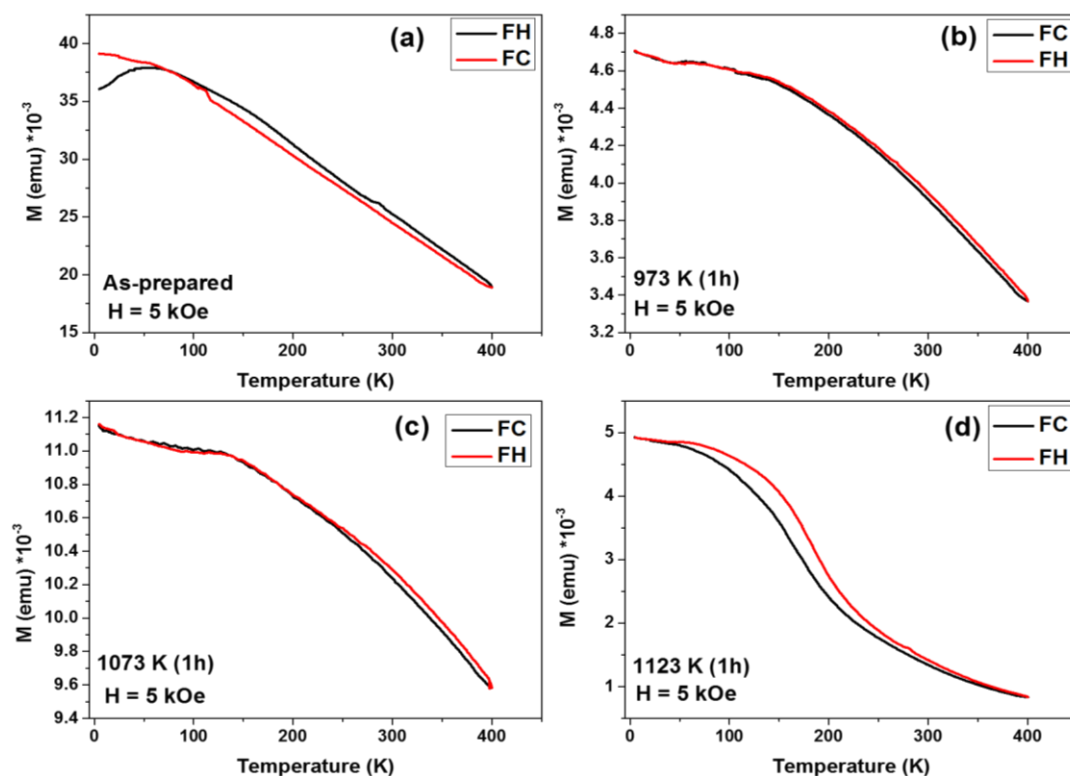


Figure 7. FC and FH temperature dependence of as-prepared (a) and different temperature annealed (b) 973 K (1h), (c) 1073 K (1h) and (d) 1123 K (1h) of Mn-Fe-P-Si-based glass-coated microwire measured at magnetic field ($H = 5$ kOe).

The observed temperature dependence of magnetic properties (H_c , FC, and FH) aligns with the established correlation between microstructures and magnetic properties in annealed samples. Furthermore, the modest variation in magnetic properties of the annealed samples is likely attributable to the influence of internal stress and average grain size on the micromagnetic structure. Further investigation into the micromagnetic structure of the post-annealed MnFePSi samples is warranted to gain deeper insights.

Our findings suggest that annealing within the temperature range of 973 K to 1123 K for one hour induces recrystallization, grain size growth, atomic ordering, and a reduction in internal stresses within the microwires. These structural modifications contribute to the enhancement of the Fe_2P phase, which is responsible for the thermomagnetic response of Mn-Fe-P-Si-based alloys. Additionally, the distinct magnetic behavior observed in the annealed Mn-Fe-P-Si glass-coated microwires can be attributed to the emergence of two distinct magnetic phases with contrasting magnetic anisotropies.

4. Conclusions

In summary, our investigation demonstrates that high-temperature annealing at 973 K, 1073 K, and 1123 K for a fixed duration of 1 hour significantly influences the magnetic and microstructural properties of Mn-Fe-P-Si glass-coated microwires. Annealing processes effectively reduce the presence of secondary phases observed in the as-prepared sample, while enhancing the dominance of the Fe_2P phase, which is a key contributor to the material's thermal magnetic response. Notably, hysteresis loop analysis reveals that annealing suppresses the metamagnetic phase transition and multistep magnetic behaviors observed in the as-prepared sample, promoting ferromagnetic ordering. This transformation results in a more homogeneous magnetic response with a significantly lower saturation field below 5 kOe compared to the 90 kOe observed in the as-prepared sample. Furthermore, the sample annealed at 973 K for 1 hour exhibits the highest coercivity value, reaching approximately 1.2 kOe, while the lowest coercivity value is observed for the sample annealed at 1123

K for 1 hour, which exhibits a value of around 30 Oe. Interestingly, the sample annealed at 1123 K for 1h FC and FH curves demonstrate notable hysteretic behavior at temperature range 50-350 K. This study underscores the potential of annealing to tailor the magnetic properties of MnFePSi glass-coated microwires, paving the way for applications that leverage these tailored properties in glass-coated microwire technology.

Author Contributions: Conceptualization, M.S. and A.Z.; methodology, M.S, V.Z.; validation, M.S., V.Z. and A.Z.; formal analysis, M.S; investigation, M.S. and A.Z.; resources, V.Z. and A.Z.; data curation M.S and V.Z; writing—original draft preparation, M.S. and A.Z.; writing—review and editing, M.S. and A.Z.; visualization, M.S. and V.Z supervision, A.Z.; project administration, V.Z. and A.Z.; funding acquisition, V.Z., and A.Z. All authors have read and agreed to the published version of the manuscript

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Conflicts of Interest: “The authors declare no conflicts of interest.”

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