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The Effect of Carbon on the Optimization of Physical Characteristics of Fe-Si-C Amorphous Ribbons

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Abstract

This article extensively investigates the effect of carbon on the physical characteristics of Fe-Si-C amorphous ribbons. A detailed analysis was conducted on the structure, morphology, electrical, magnetic, and thermal properties of Fe-Si-C amorphous ribbon samples with varying carbon content. The study explores how changes in carbon concentration influence magnetic parameters such as saturation magnetization and coercive force, as well as the impact of carbon on the electrical resistance and thermal stability of the amorphous structure. The results indicate that the distribution of carbon within the structure and its interactions with other elements significantly affect the overall morphology and physical properties of the ribbons. Specifically, carbon content enhances structural stability and reduces the tendency of the amorphous phase to crystallize, thereby improving stability under high-temperature conditions. The potential application areas of the studied amorphous ribbons, including energy conversion and magnetic sensors, are also discussed. This work provides deeper insights into the role of carbon in adapting Fe-Si-C amorphous ribbons for various applications and serves as a foundation for future research.

Keywords: Fe-Si-C amorphous ribbons, carbon effect, soft magnetic properties, thermal stability, morphology and structure.

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Fe-Si-C tərkibli amorf lentlərin fiziki xarakteristikalarının optimallaşdırılmasına karbonun təsiri

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Xülasə

Bu məqalədə Fe-Si-C tərkibli amorf lentlərin fiziki xarakteristikalarına karbonun təsiri geniş şəkildə araşdırılıb. Tədqiqatda müxtəlif karbon tərkibli Fe-Si-C amorf lent nümunələrinin strukturu, morfologiyası, elektrik, maqnit və termik xüsusiyyətləri üzərində dərin təhlillər aparılıb. Karbonun miqdarının dəyişməsi ilə lentlərin doyma maqnitlənməsi və koersitiv qüvvəsi kimi maqnit parametrlərinin necə dəyişdiyi, həmçinin karbonun amorf strukturun elektrik müqavimətinə və temperatur stabilliyinə təsiri öyrənilib. Tədqiqatın nəticələri göstərir ki, karbonun struktur daxilində paylanması və onun digər elementlərlə qarşılıqlı əlaqəsi lentin ümumi morfoloji və fiziki xüsusiyyətlərinə əhəmiyyətli təsir göstərir. Xüsusilə, karbonun miqdarı strukturda stabilliyi artıraraq amorf fazanın kristallaşma meyilini zəiflədir. Beləliklə, lentin yüksək temperatur şəraitində stabilliyini təmin edir. Öyrənilən amorf lentlərin mümkün tətbiq sahələri, o cümlədən enerji çevrilməsi və maqnit sensorları kimi mühüm texnologiyalarda istifadəsi üçün əhəmiyyəti müzakirə edilib. Bu iş karbonun Fe-Si-C tərkibli amorf lentlərinin müxtəlif tətbiqlər üçün uyğunlaşmasında oynadığı rolu daha yaxşı başa düşməyə imkan yaradır və gələcək tədqiqatlar üçün baza rolunu oynayır.

Açar sözlər: Fe-Si-C amorf lentlər, karbonun təsiri, maqnityumşaq xüsusiyyətlər, termal stabillik, morfologiya və struktur.

Влияние углерода на оптимизацию физических характеристик аморфных лент состава Fe-Si-C

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Аннотация

В статье подробно исследуется влияние углерода на физические характеристики аморфных лент состава Fe-Si-C. Проведен глубокий анализ структуры, морфологии, электрических, магнитных и термических свойств образцов аморфных лент Fe-Si-C с различным содержанием углерода. Изучено, как изменение концентрации углерода влияет на магнитные параметры, такие как насыщение намагничивания и коэрцитивная сила, а также влияние углерода на электрическое сопротивление и термическую стабильность аморфной структуры. Результаты показывают, что распределение углерода в структуре и его взаимодействие с другими элементами оказывают значительное влияние на общую морфологию и физические свойства лент. В частности, содержание углерода повышает структурную стабильность и снижает склонность аморфной фазы к кристаллизации, обеспечивая стабильность при высоких температурах. Обсуждаются возможные области применения изученных аморфных лент, включая преобразование энергии и магнитные датчики. Эта работа предоставляет более глубокое понимание роли углерода в адаптации аморфных лент Fe-Si-C для различных применений и служит основой для будущих исследований.

Ключевые слова: аморфные ленты Fe-Si-C, влияние углерода, магнитно-мягкие свойства, термическая стабильность, морфология и структура.

Introduction

Amorphous magnetic materials have garnered significant interest in recent years in engineering, electronics, and energy sectors. Unlike crystalline structures, amorphous magnetic materials exhibit unique advantages, including high magnetic permeability, low energy loss, and excellent corrosion resistance [1-3]. Among these, Fe-Si-C-based amorphous ribbons stand out due to their ability to combine enhanced magnetic properties with thermal stability, making them promising candidates for applications in energy conversion and magnetic shielding [4-6]. The inclusion of carbon in Fe-Si-C amorphous ribbons significantly influences their magnetic, electrical, and thermal conductivity properties, rendering them particularly attractive for high-performance applications [7].

The addition of carbon to Fe-Si-C amorphous ribbons aims to alter their structure and morphology, thereby affecting their physical properties. Incorporating carbon can induce substantial changes in characteristics such as electrical resistivity, magnetic permeability, and thermal stability [8-10]. These modifications are crucial for applications in areas like high-frequency transformers, sensors, and other energy-related fields. Carbon can induce specific changes in the structure of Fe-Si-C amorphous ribbons, potentially regulating their degree of crystallinity and influencing magnetic properties [11].

A review of the literature reveals extensive studies on improving the properties of amorphous materials through various elements, especially carbon. Research demonstrates that changes in carbon content significantly impact structural stability and magnetic properties in amorphous materials. Previous studies [12] show that carbon concentration in Fe-Si-C ribbons strongly affects parameters such as magnetic permeability, coercive force, and saturation magnetization. Other research [5] indicate that controlling carbon content enables tailoring Fe-Si-C amorphous ribbons for specific applications.

Aim of work

The research aims to investigate the structure, morphology, and electrical and magnetic properties of Fe-Si-C amorphous ribbons and compare their application potential with crystalline Fe-Si (electrotechnical steel) materials. It seeks to explore how compositional changes affect the electrical and magnetic characteristics of Fe-Si-C amorphous ribbons, including specific electrical resistance, coercive force, residual magnetization, and saturation magnetization. Additionally, the study examines the conditions under which thermal stability is compromised and crystallization tendencies occur. It also identifies the optimal carbon content for industrial applications and highlights the advantages of Fe-Si-C amorphous ribbons over crystalline Fe-Si materials.

Materials

Fe-Si-C amorphous ribbon samples were synthesized using the rapid quenching method with a cooling rate of 10^5-10^6 K/s. This process enables the alloy to retain an amorphous structure. Samples with compositions Fe92Si6C2 and Fe93Si6C1 were prepared. High-purity Fe, Si, and C components were mixed in specific ratios, melted, and rapidly cooled under pressure to form ribbons.

Methods

Structural and Morphological Analysis: X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) were employed to analyze structural and morphological properties. XRD determined the crystalline and amorphous phases of the ribbons, while SEM analyzed surface structure, microstructure, homogeneity, and elemental distribution.

Electrical Property Analysis: The four-point probe method was used to measure electrical resistivity, ensuring precise and reliable results. Two probes created the current, while the other two measured voltage to assess surface conductivity homogeneity.

Magnetic Property Analysis: Magnetic properties were evaluated using a Vibrating Sample Magnetometer (VSM). Parameters like coercive force (Hc), residual magnetization (Mr), and saturation magnetization (Ms) were measured to determine magnetic behavior and losses.

Thermal Stability and Resistance Analysis: Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) were conducted to assess thermal decomposition and crystallization temperatures. DSC evaluated the temperature range in which amorphous structures transition to crystalline phases, while TGA determined thermal stability and resistance to oxidation.

Discussion of Results

Structural and Morphological Properties: XRD analyses confirmed that the synthesized Fe92Si6C2 and Fe93Si6C1 ribbons possess an amorphous structure. Broad peaks in the XRD patterns indicated the presence of an amorphous phase (Figure 1). This confirms that rapid quenching effectively prevents the formation of crystalline structures, retaining the material in an amorphous state.

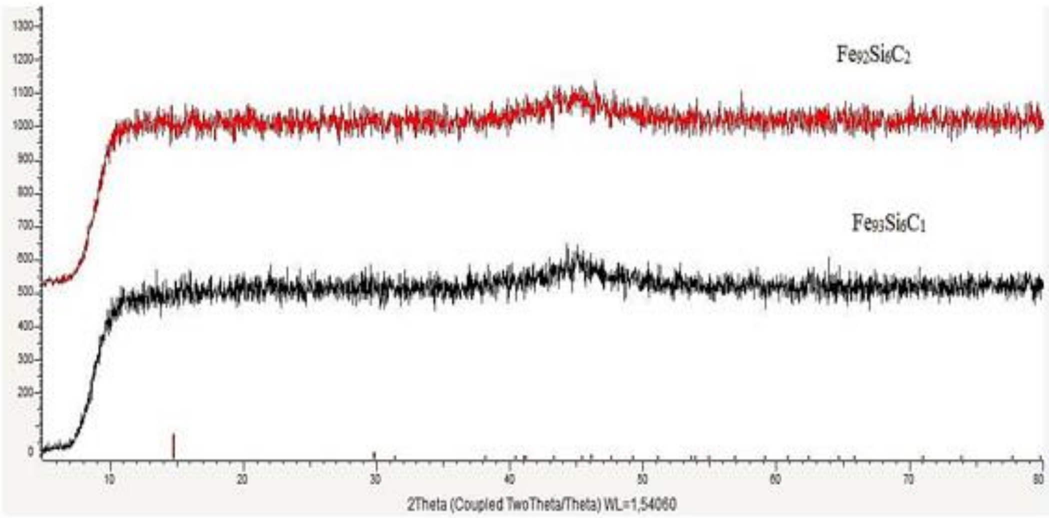

Figure 1 – XRD analysis results of the samples after the initial production process

SEM Analysis: SEM analysis revealed that the surface of the ribbons exhibits a homogeneous and fine-grained structure. These characteristics indicate that amorphous ribbons possess uniform magnetic and electrical properties, enhancing their prospects as high-performance materials.

Electrical Properties: Measurements conducted using the four-point probe method demonstrated that the electrical resistivity of Fe-Si-C amorphous ribbons is significantly higher compared to crystalline Fe-Si materials (Table 1). This higher resistivity is attributed to the amorphous structure, which negatively affects electrical conductivity. The elevated resistivity of amorphous materials enhances their suitability for energy storage and electronics, particularly in high-frequency applications. Furthermore, high resistivity reduces eddy current losses, enabling magnetic cores to operate more efficiently.

Magnetic Properties: The magnetic properties of $Fe_{92}Si_6C_2$ and $Fe_{93}Si_6C_1$ amorphous ribbons were extensively studied using a Vibrating Sample Magnetometer (VSM). The results are summarized in Table2.

Table 1 – Specific Electrical Resistivity of Fe-Si-C Amorphous Ribbons

Parameter	$Fe_{92}Si_6C_2$	$Fe_{93}Si_6C_1$	Crystalline Fe-Si (Electrical Steel)
Specific Resistivity	~130 - 150 μΩ·cm	~135 - 155 μΩ·cm	~45 - 55 μΩ·cm

Table 2 – Magnetic Properties of $Fe_{92}Si_6C_2$ and $Fe_{93}Si_6C_1$ Amorphous Ribbons

Parameter	Fe92Si6C2	Fe93Si6C1	Crystalline Fe-Si (Electrical Steel)
Coercivity (Hc)	~ 0,03 - 0,05 Oe	~0,02 - 0,04 Oe	~0,1 - 0,2 Oe
Magnetic Permeability (μ)	~60,000 - 120,000	~70,000 - 110,000	~4,000 - 30,000
Remanent Magnetization (Br)	~0.7 - 0.9 T	~0.75 - 0.85 T	~1.0 - 1.2 T
Saturation Magnetization (Bs)	~1.5 - 1.6 T	~1.55 - 1.65 T	~1.8 - 2.0 T

Coercivity (Hc): The coercivity of $Fe_{92}Si_6C_2$ and $Fe_{93}Si_6C_1$ ribbons is significantly lower compared to crystalline Fe-Si materials, making them suitable as soft magnetic materials. This low coercivity makes them ideal for applications requiring high magnetic permeability, such as transformers and sensors.

Remanent and Saturation Magnetization (Br, Bs): The saturation magnetization of amorphous ribbons is comparable to that of crystalline Fe-Si materials. The favorable saturation magnetization enables high magnetic permeability under strong magnetic fields, making $Fe_{92}Si_6C_2$ and $Fe_{93}Si_6C_1$ ribbons promising for high-performance magnetic core applications.

Thermal Stability and Resistance:

The thermal stability and glass transition temperature (Tg) of the ribbons were assessed using Differential Scanning Calorimetry (DSC). The analysis was conducted in a nitrogen atmosphere with a heating rate of 10 K/min from room temperature to 600 K. The DSC curve exhibited an endothermic peak corresponding to Tg at approximately 480 K, with no exothermic peaks (indicative of crystallization) observed up to 490–500 K, confirming excellent thermal stability (Fig. 2).

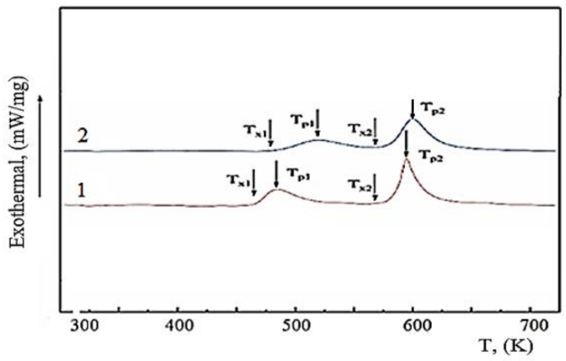

Figure 2 – DSC analysis results of both samples: 1-$Fe_{92}Si_6C_2$; 2-$Fe_{93}Si_6C_1$

To determine thermal degradation behavior, Thermogravimetric Analysis (TGA) was performed in an air atmosphere with a heating rate of 10 K/min up to 1100 K. The TGA curve indicated minimal weight loss below 670 K, affirming the thermal stability of the ribbons. Significant weight loss occurred above 870 K, marking the onset of thermal degradation. The TGA results demonstrate that Fe-Si-C amorphous ribbons possess high oxidation resistance, ensuring stability under atmospheric conditions. This characteristic makes them suitable for energy storage, electrical, and magnetic core applications, as well as electronic components operating in high-temperature environments.

The results of the research show that $Fe_{92}Si_6C_2$ and $Fe_{93}Si_6C_1$ -based amorphous ribbons possess significant characteristics that allow them to compete with crystalline Fe-Si materials, such as low coercivity, high magnetic permeability, high electrical resistance, and excellent temperature stability. Carbon plays a crucial role in stabilizing the amorphous structure and influencing the characteristics of the ribbons. The higher carbon content in $Fe_{92}Si_6C_2$ improves the homogeneity of the amorphous structure, resulting in lower resistance and enhanced magnetic properties. In contrast, the reduced carbon content in $Fe_{93}Si_6C_1$ leads to slight inhomogeneity, which manifests as an increase in electrical resistance. Overall, the research confirms that both $Fe_{92}Si_6C_2$ and $Fe_{93}Si_6C_1$ amorphous ribbons exhibit superior electrical and magnetic properties compared to traditional crystalline Fe-Si alloys. The results show that small changes in composition can have a significant impact on the properties of the ribbons. Future research should focus on further investigation and optimization of these changes.

Thus, Fe-Si-C amorphous ribbons possess a range of superior properties compared to crystalline Fe-Si (electrical steel) materials and could potentially deliver more efficient results in various fields.

Conclusion

This study evaluated the structure, electrical, magnetic, and thermal properties of $Fe_{92}Si_6C_2$ and $Fe_{93}Si_6C_1$ amorphous ribbons, comparing their performance to crystalline Fe-Si materials. The following conclusions were given:

Structure and Morphology: The rapid quenching process resulted in the amorphous structure of Fe-Si-C ribbons, creating a homogeneous microstructure on the surface and enhancing their stability.

Electrical Properties: The high electrical resistivity of Fe-Si-C amorphous ribbons reduces eddy current losses, improving efficiency in high-frequency electronics and magnetic cores. This makes them particularly advantageous for energy storage and electronic applications.

Magnetic Properties: The low coercivity and favorable saturation magnetization of $Fe_{92}Si_6C_2$ and $Fe_{93}Si_6C_1$ ribbons render them suitable as soft magnetic materials for applications requiring high magnetic permeability, such as magnetic cores, sensors, and transformers.

Thermal Stability and Resistance: The high crystallization temperature and oxidation resistance of Fe-Si-C amorphous ribbons ensure stability even at elevated temperatures, making them ideal for use in high-temperature technologies.

The study highlights that carbon plays a critical role in stabilizing the amorphous structure and influencing ribbon properties. $Fe_{92}Si_6C_2$, with a higher carbon content, exhibits improved homogeneity and magnetic properties. Conversely, the slightly reduced homogeneity in $Fe_{93}Si_6C_1$ due to lower carbon content increases electrical resistivity.

Overall, both $Fe_{92}Si_6C_2$ and $Fe_{93}Si_6C_1$ amorphous ribbons demonstrate superior electrical and magnetic properties compared to traditional crystalline Fe-Si alloys. Optimizing composition and understanding structure-property relationships can further enhance their potential for advanced technological applications.

Conflict of Interests

The authors declare there is no conflict of interests related to the publication of this article.

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