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Structure transformation in amorphous Fe-B ribbon under laser scanning

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Amorphous $Fe_{86}B_{14}$ alloy produced by the melt quenching technique was processed by pulsed fiber laser in scanning mode with various scanning speeds and laser power. The X-ray diffraction method was used to study the laser-induced structure evolution in the amorphous ribbon. Nanosized grains of α-Fe phase were observed as a result of partial crystallization.

Keywords: Fe-B amorphous alloy, laser scanning, nanocrystallization, X-ray diffraction.

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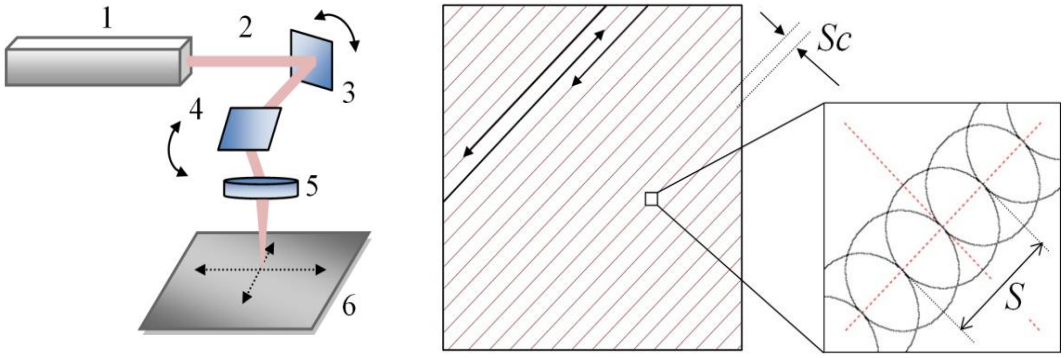
Introduction

In recent decades, amorphous Fe-based alloys attracted the attention of many researchers due to their unique properties associated with a disordered structure and a tendency to form fine nanostructures in the presence of appropriate impurities. Lots of studies were devoted to studying the laser-induced structure evolution, laser-assisted crystallization processes, and laser treatment influence on the physical properties of the multi-component Fe-Si-B amorphous alloys with Ni, Cr, Mo, Mr, Co and other impurities [1,2,3]. Most of the authors deal with the laser treatment of amorphous FeCuNbSiB alloys, also known as Finemet-type alloys, that exhibit excellent soft magnetic properties [4,5,6]. The others focus their research on Fe-Si-B and Fe-Si-B-Cu glasses [7,8,9,10] under laser heating and processing. However, significantly less attention was paid to Fe-B amorphous alloy under laser treatment. Only a few works focused on the laser irradiation of this binary alloy were found [11,12,13]. Nevertheless, amorphous Fe-B alloys have been of much interest because they can be formed in a wide concentration range by rapid cooling, and one finds an anomalous effect of boron concentration on their physical properties. Besides, studying the laser-induced structure transformation processes in Fe-B system can supplement and expand the conception of interaction between high-energy radiation and metastable condensed matter. In this regard, the aim of this study is to explore the structure transformation and crystallization behaviour in Fe-B amorphous ribbon induced by pulsed laser irradiation.

I. Materials and methods

Amorphous $Fe_{86}B_{14}$ alloy was produced by the melt quenching technique in the form of a ribbon thickness of 25 μm and width of 5 mm. A pulsed fiber laser with wavelength λ = 1064 nm and maximum power P = 20 W was used to irradiate the ribbon samples in scanning mode. During irradiation, the samples of the ribbon were fixed on a metal substrate and placed at the focal plane of the lens, air atmosphere. Schemes of laser equipment and surface scanning are shown in Fig.1, where 1 – fiber laser, 2 – laser beam, 3 and 4 – galvanoscaners, 5 – lens, 6 – ribbon sample, *Sc*– scanning step, and *S*– pulse step. The parameters of the laser processing are listed in Table 1.

The structure changes in the irradiated ribbon were studied using the X-ray diffraction method (XRD) (CuKα radiation, $\lambda = 0.1541$ nm). The X-ray beam with a diameter of about 5 mm to 6 mm was directed on the irradiated surface of the ribbon. Phases, which crystallized under laser irradiation, were determined by interpretation of diffraction peak positions. The



a b

Fig. 1. Schemes of laser equipment (a) and surface scanning (b).

Table 1.

Parameters of laser scanning

№	Beam speed, mm/s	Laser power, W	Pulse frequency, kHz	Pulse energy, mJ	Pulse step, μm	Scanning step, μm	Energy density, J/mm^2
1	500	8	20	0.4	25	50	0.32
2	500	10	20	0.5	25	50	0.40
3	500	12	20	0.6	25	50	0.48
4	1000	12	20	0.6	50	50	0.24
5	2000	14	20	0.7	100	50	0.14

interplanar distances (*d*-spacing) were calculated by the Wulff–Bragg's condition: $2d \sin\theta = n\lambda$. The fraction of each phase X and the average grain size of the crystallites L_{cr} were determined using formulas:

$$X = \frac{I_{cr}}{I_{cr} - I_{am}} \quad (1)$$

where I_{cr} and I_{am} – the integral intensities for the crystalline and amorphous phases, respectively.

$$L_{cr} = \frac{\lambda}{\beta \cos(\theta)} \quad (2)$$

where $\beta = B - b$; B and b – the full width of half peak for the investigated and reference samples respectively, 2θ – scattering angle.

II. Results and discussion

In recent years, using nanosecond laser pulses for precision micromachining has drawn big interest. Many studies have demonstrated the advantages of nanosecond laser pulses over longer laser pulses, including the negligible heat-affected zone, ablation threshold, and efficiency. Combining laser parameters like laser power, wavelength, laser beam speed, pulse frequency, repetition rate, etc, various heating conditions can be achieved leading to various structure transformations and property changes. Based on literature data and our previous results [14,15,16], we chose the modes shown in Table 1 for the irradiation of the Fe-B amorphous ribbon. Using the X-ray diffraction method, we revealed partial crystallization of irradiated samples. Reflexes that appeared on the diffraction patterns after laser scanning with 500 mm/s (Fig. 2) coincide with α-Fe (bcc phase, rt modification). Table 2 shows data for calculated diffraction lines (intensity, h k l indexes and *d*-spacing) for α-Fe phase and 2θ and *d*-spacing for samples 1, 2, and 3 from Table 1. As shown by Matsuura [17] in Fe-B alloys with 14 at.% boron, a two-stage crystallization occurs under heating with a rate 20 K*min^{-1}. The first crystallization peak, which was observed in a temperature range of about 650 – 670 K, was due to the formation of α-Fe, and the second peak, which was observed in a temperature range of about 750-770 K, due to the formation of b.c. tetragonal Fe_3B. In our study, no reflexes that coincide with the Fe_3B phase were observed, so we achieved only the first-stage crystallization by laser scanning the ribbon surface. A detailed study of the main maxima of the X-ray diffraction patterns, shown in Fig. 2 (right images), was carried out by fitting the experimental data with two-peak Lorentzian functions. The wider Lorentzian peak corresponds to the amorphous phase, while the second and smaller one corresponds to the crystalline α-Fe.

Increasing the laser beam speed up to 1000 mm/s and 2000 mm/s resulted in decreasing energy density and reducing percentage in crystalline fraction. Diffraction patterns of the samples scanned with these speeds are presented in Fig.3. Quite weak reflexes from the α-Fe phase can be discerned on the patterns; however, the two-peak Lorentzian function correctly fits the experimental data indicating the formation of minor crystalline phase in an amorphous matrix.

The percentage of the crystalline fraction formed in laser-scanned samples was calculated by formula (1), and the average size of α-Fe crystallites was calculated by formula (2). The results of the calculations are presented in Table 3. Non-linear dependencies of percentage and

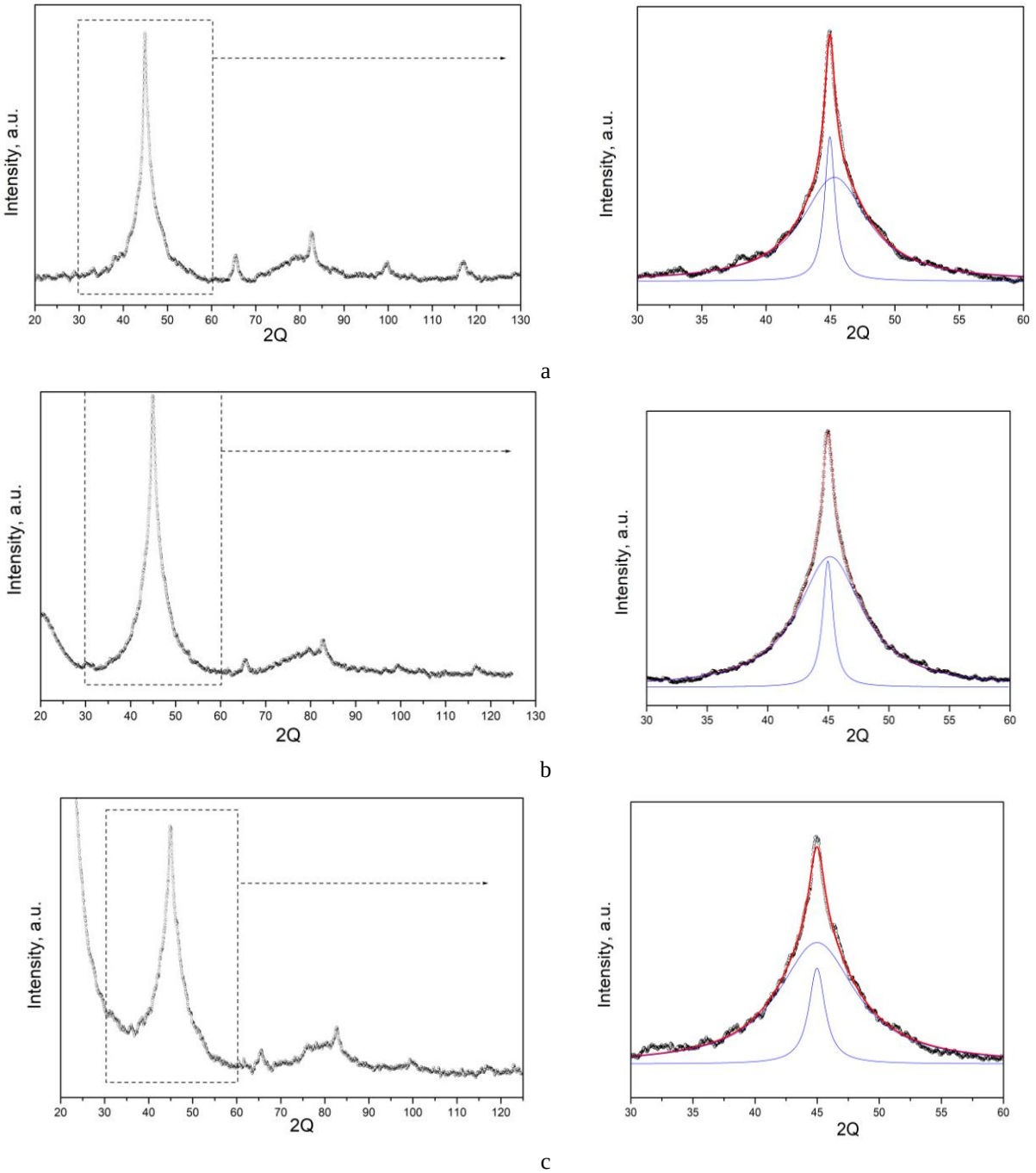


Fig. 2. X-ray diffraction patterns of $Fe_{86}B_{14}$ ribbon samples irradiated at laser beam speed 500 mm/s, and laser power 8 W (a), 10 W (b), 12 W (c).

Table 2.

Diffraction lines of α- Fe crystalline phase observed after irradiation with beam speed 500 mm/s

α- Fe calc.			Sample 1		Sample 2		Sample 3	
Int. %	hkl	*d*, nm	2*θ*, deg.	*d*, nm	2*θ*, deg.	*d*, nm	2*θ*, deg.	*d*, nm
100	101	0.2023	44.75	0.1973	44.75	0.1973	44.86	0.1968
15	020	0.1431	65.31	0.1352	65.43	0.1349	65.30	0.1352
28	211	0.1168	82.67	0.1068	82.49	0.1070	82.63	0.1068
10	220	0.1011	99.47	0.0888	99.20	0.0890	99.24	0.0889
18	013	0.0905	116.88	0.0756	116.64	0.0757	116.86	0.0755

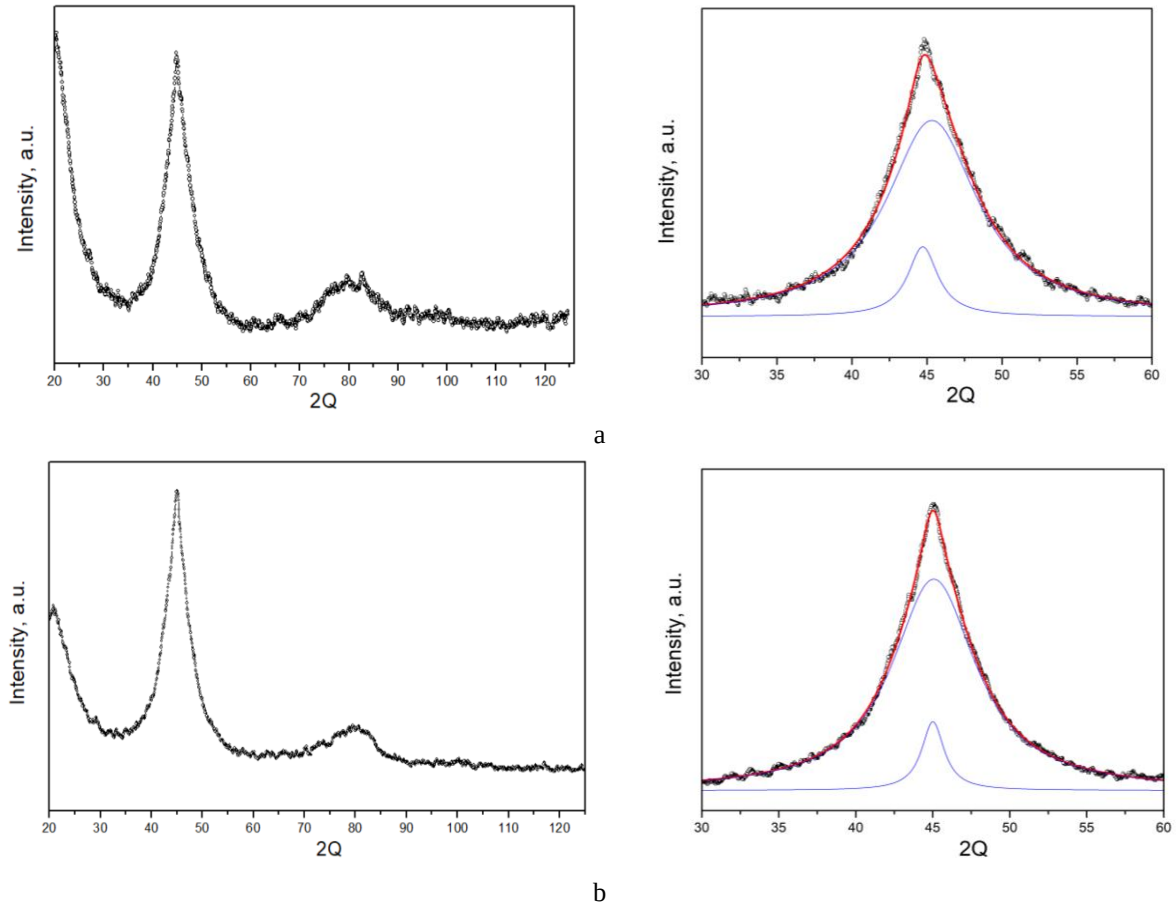


Fig. 3. X-ray diffraction patterns of $Fe_{86}B_{14}$ ribbon samples irradiated at laser beam speed 1000 mm/s, and laser power 12 W (a) and laser beam speed 2000 mm/s, and laser power 14 W (b).

Table 3.

Calculated fraction (X), average grain size (L_{cr}) and cell parameter (a) of the α-Fe phase

№	Beam speed, mm/s	Laser power, W	Energy density, J/mm^2	β	L_{cr}, nm	a, nm	X, %
1	500	8	0.32	1.80	113.3	0.2861	23.6
2	500	10	0.40	2.53	17.1	0.2860	12.9
3	500	12	0.48	3.33	12.2	0.2860	11.8
4	1000	12	0.24	4.74	11.1	0.2858	4.9
5	2000	14	0.14	4.85	9.0	0.2853	3.5

grain size of crystalline phase on energy density can be revealed. This nonlinearity can be caused by uneven temperature distribution and indicates complicated processes of structure evolution. A similar non-linear percentage dependence on pulse energy was observed in [18] for amorphous FeNbCuSiB alloy.

Conclusions

The first-stage crystallization of α-Fe can be achieved in $Fe_{86}B_{14}$ amorphous ribbon by laser scanning the surface with an energy density of about 0.14-0.48 J/mm^2. Due to the local crystallization process, the amorphous-nanocrystalline composite material can be formed with a controlled distribution of crystallites. Increasing energy density does not result in expected crystalline fraction increasing as well as Fe_3B crystallization, at least, under applied laser parameters. This indicates complicated processes of structure evolution that have yet to be studied in our further research.

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Структурні перетворення в аморфній стрічці Fe-B при лазерному скануванні

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Аморфний сплав $Fe_{86}B_{14}$, отриманий методом загартування з розплаву, обробляли імпульсним волоконним лазером у режимі сканування з різною швидкістю сканування та потужністю лазера. Методом рентгенівської дифракції досліджено індуковану лазером еволюцію структури аморфної стрічки. Нанорозмірні зерна фази α-Fe спостерігалися в результаті часткової кристалізації.

Ключові слова: аморфний сплав Fe-B, лазерне сканування, нанокристалізація, рентгенівська дифракція.