

# Fe-based amorphous soft magnetic powders fabricated by water atomization

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**Abstract.** Fe-Si-B-Cr-Mn-Al powders were prepared by water atomization. We studied the phase, morphology and properties of the atomized powders. Experiment results present that the completely amorphous phase is achieved in powders having a diameter less than 150  $\mu\text{m}$ . The morphology of most of powders is spherical or elliptical. The atomized powder possess good thermal stability and excellent soft magnetic properties. Their average saturation magnetization is as high as 151.2 emu/g.

**Keywords:** metallic glass; soft magnetic; powder; water atomization.

## 1 Introduction

Magnetic materials are of fundamental importance for several applications in the electrical and electronic industries [1]. Fe-based metallic glass has desirable soft magnetic properties of high saturation magnetization, low coercivity, and high electrical resistivity [2]. The Fe-based amorphous alloy has been intensely investigated. In 1982, the first amorphous alloy with a composition of  $\text{Fe}_{75}\text{Si}_{10}\text{B}_{15}$  was produced by Inoue, and its diameter is 0.27 mm. Then in 1995  $\text{Fe}_{73}\text{Al}_5\text{Ga}_2\text{P}_{11}\text{C}_5\text{B}_4$  metallic glass with a diameter of 1 mm was prepared [4]. Many other Fe-based amorphous alloy were subsequently synthesized, such as,  $\text{Fe}_{65}\text{Co}_{10}\text{Ga}_5\text{P}_{12}\text{C}_4\text{B}_4$  [5],  $\text{Fe}_{62.8}\text{Co}_{10}\text{B}_{13.5}\text{Si}_{10}\text{Nb}_3\text{Cu}_{0.7}$  [6],  $\text{Fe}_{71.2}\text{C}_{7.0}\text{Si}_{3.3}\text{B}_{5.5}\text{P}_{8.7}\text{Cr}_{2.3}\text{Al}_{2.0}$  [7] and  $\text{Fe}_{69}\text{Cr}_2\text{Mo}_5\text{P}_{12}\text{C}_{10}\text{B}_2$  [8].

In the development of Fe-based alloys, the Fe-Si-B system is frequently researched, because of the fairly high saturation magnetization, no intrinsic magneto-crystalline anisotropy, low cost and the remarkable productivity [9]. But, its glass forming ability is very poor, and the thickness of ribbons made by melt-spinning is usually smaller than 25  $\mu\text{m}$ . As a result, the amorphous alloy in large size is difficult to be prepared, which is one of the main bottleneck restricting the application of this amorphous alloy [10,11]. Powder metallurgy is a very good method to prepare bulk amorphous alloy, because the size and shape of alloy are easy to be controlled in the process of powder metallurgy [12, 13].

It is well known that the first procedure of powder metallurgy is to prepare high quality amorphous powders. In this work, we fabricated Fe-Si-B-Cr-Mn-Al metallic glass powders by using water-atomization. The Cr, Al, Mn elements are added to improve the glass forming ability. The phase, morphology and properties of the atomized powders were examined.

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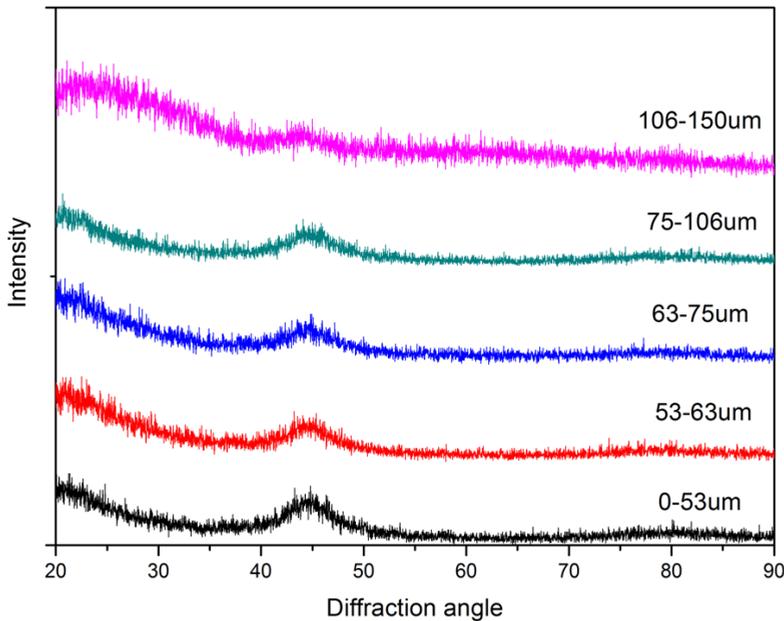
## 2 Experimental

The powders with a composition of  $\text{Fe}_{76}\text{Si}_{13}\text{B}_7\text{Cr}_2\text{Mn}_1\text{Al}_1$  were fabricated by water atomization. After screening, the powder particles were divided into the following groups according to the size: 0-53  $\mu\text{m}$ , 53-63  $\mu\text{m}$ , 63-75  $\mu\text{m}$ , 75-106  $\mu\text{m}$ , and 106-150  $\mu\text{m}$ . The powders with diameter above 150  $\mu\text{m}$  were discarded. Examination of phase and the morphology were carried out by using X-ray diffractometry (XRD) and scanning electron microscopy (SEM), respectively. The thermal stability was examined by differential scanning calorimeter (DSC). The DSC trace of powders was performed at a heating rate of 10 K/s in an Ar<sub>2</sub> atmosphere. The magnetic property was measured by vibrating sample magnetometer (VSM) with maximum applied field of 18000Oe.

## 3 Results and discussion

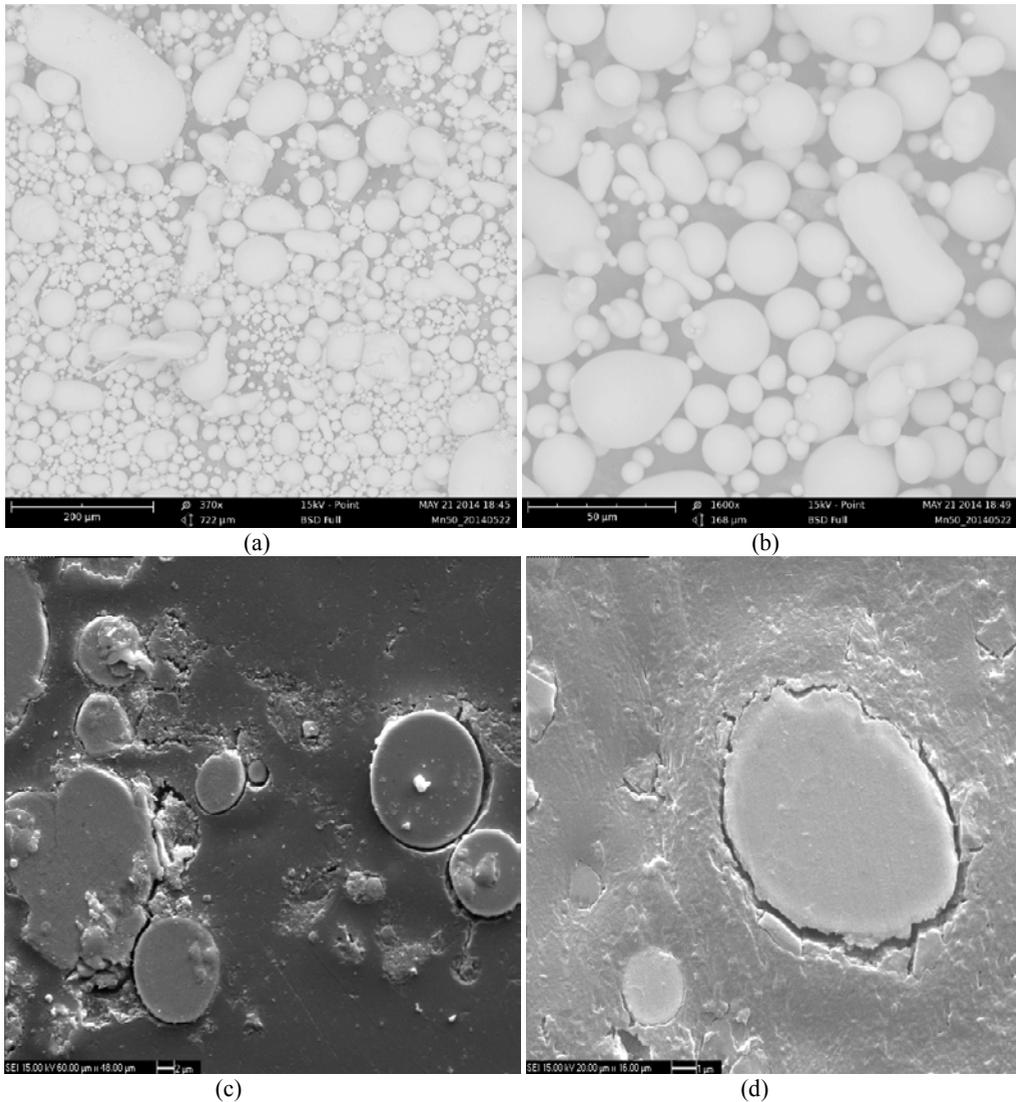
### 3.1 Phase and morphology of alloy powders

Fig. 1 shows the XRD of the amorphous powders with different particle size. The typical XRD patterns of amorphous phase can be observed in all the powders with different size. It means that the fabricated powders less than 150 $\mu\text{m}$  in diameter are fully amorphous without the crystalline phases. The fast cooling rate can be achieved in the water-atomization process to suppress the formation of crystalline phase in  $\text{Fe}_{76}\text{Si}_{13}\text{B}_7\text{Cr}_2\text{Mn}_1\text{Al}_1$  alloy [10, 14].



**Figure 1.** XRD patterns of the as-atomized  $\text{Fe}_{76}\text{Si}_{13}\text{B}_7\text{Cr}_2\text{Mn}_1\text{Al}_1$  alloy powders.

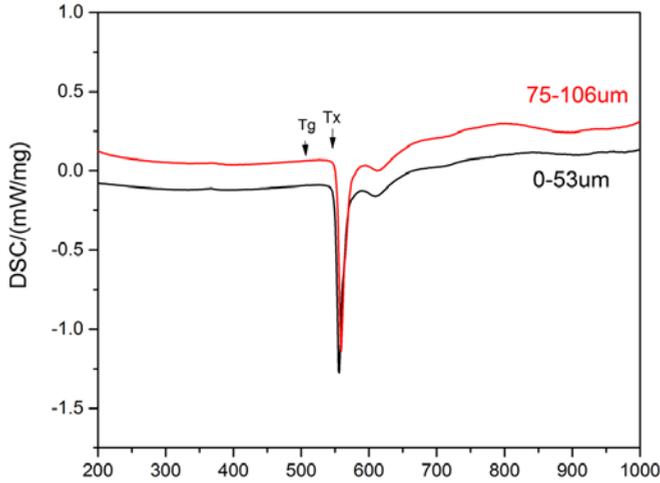
Fig. 2 shows the surface morphology and cross section of the as-atomized  $\text{Fe}_{76}\text{Si}_{13}\text{B}_7\text{Cr}_2\text{Mn}_1\text{Al}_1$  alloy powders. Fig. 2a and 2b present the surface morphology of the powders. It can be seen that most of the powders are spherical or elliptical apart from several jointed large powders. The difference in shape is due to various disintegrating and cooling conditions. Small particles have a fast cooling rate, and complete solidification occurred before they turn to be spherical, while large particles have enough time to become spherical under the action of the surface tension [15]. Moreover, the cross section of powders shows a very smooth structure (fig.2c and 2d). No tendency of crystalline phases can be found. This is consistent with the results of XRD (fig.1).



**Figure 2.** Surface and cross section of the as-atomized  $\text{Fe}_{76}\text{Si}_{13}\text{B}_7\text{Cr}_2\text{Mn}_1\text{Al}_1$  powders. in different zoom scales; surface:(a) small;(b)large; cross section:(c)small;(d) large.

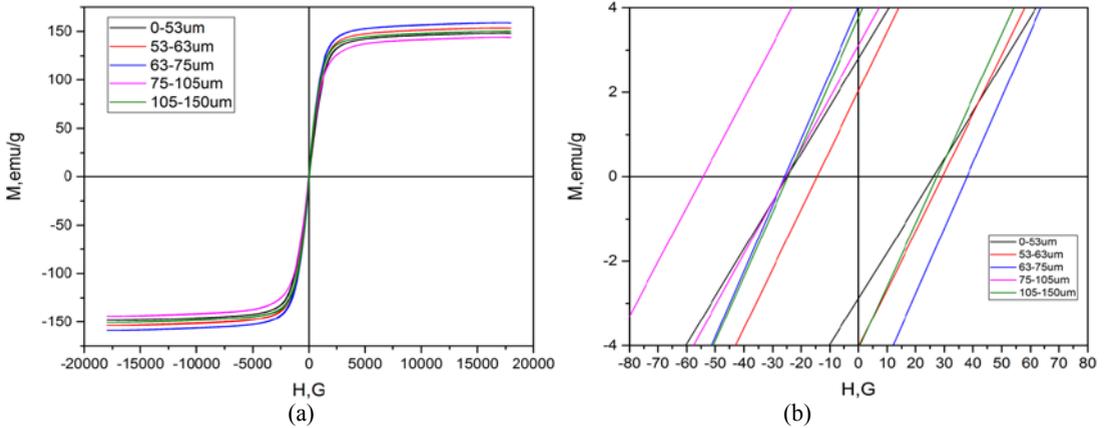
### 3.2 Thermal stability and magnetic property

Fig. 3 shows the DSC trace of the as-atomized  $\text{Fe}_{76}\text{Si}_{13}\text{B}_7\text{Cr}_2\text{Mn}_1\text{Al}_1$  alloy powders in the two groups of 0-53  $\mu\text{m}$  and 76-105  $\mu\text{m}$ . It can be seen that the measured curves are almost the same for the two groups of powders. It indicates that powder size has no effect on the thermal stability. The glass transition temperature  $T_g$ , the crystallization temperature  $T_x$  and  $\Delta T_x$  ( $T_x - T_g$ ) of the powders are 743 K, 776 K and 33 K respectively. These powders have good thermal stability. And the glass transition region is about 21 K smaller than that of the as-cast material, reported in Ref [16].



**Figure 3.** DSC trace of the as-atomized  $Fe_{76}Si_{13}B_7Cr_2Mn_1Al_1$  powders.

Fig. 4 shows the hysteresis loops of the five grouped as-atomized  $Fe_{76}Si_{13}B_7Cr_2Mn_1Al_1$  glass powders. Table 1 presents the corresponding values of saturation magnetization and coercivity of the as-atomized powder. The five grouped powders possess the similar saturation magnetization and coercivity. The values of saturation magnetization are only varied in a small range of 144.1-159.0 emu/g at an average of 151.2 emu/g; the values of coercivity are varied in a small range of 23.6-25.4 Oe at the average of 24.4 Oe.



**Figure 4.** Hysteresis loops of the five grouped as-atomized  $Fe_{76}Si_{13}B_7Cr_2Mn_1Al_1$  glass powders. (a): the hysteresis loops;(b): coercivity.

In order to improve the glass forming ability of Fe–Si–B system amorphous alloy, the Cr, Al, Mn elements were added into the Fe–Si–B system amorphous alloy, which resulting in a remarkable decrease in the saturation magnetization, and the saturation magnetization is lower than the pure Fe–Si–B amorphous alloys. So it is difficult to achieve a good combination of all the desired features in one alloy composition. If we wish to attain the high saturation magnetization, then the alloying elements should maintain low level.

**Table 1.** The saturation magnetization and coercivity of the as-atomized powders

Size Test	0-53	53-63	63-75	75-105	105-150	Average	Error
Ms(emu/g)	148.4	153.8	159.0	144.1	150.5	151.2	<0.5
Hc(Oe)	24.8	23.6	25.4	23.7	24.6	24.4	<0.5

## 4 Conclusions

This paper studied the  $\text{Fe}_{76}\text{Si}_{13}\text{B}_7\text{Cr}_2\text{Mn}_1\text{Al}_1$  alloy powders that prepared by water atomization. Phase analysis shows that the completely amorphous phase is generated in the powders less than 150  $\mu\text{m}$  in diameter. It means that metallic glass powders can be successfully manufactured by water atomization. And it is also can be concluded that the atomized powders have good thermal stability and soft magnetic properties. The glass transition temperature  $T_g$  of 743 K and the crystallization temperature  $T_x$  of 776 K are obtained in powders regardless of the variation of powder size. The maximum value of saturation magnetization is as high as 159.0 emu/g and the average value of different particle sizes is 151.2 emu/g.

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