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Effect of boron content on microstructures and magnetic properties of hot-rolled Pr-Fe-B magnets

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Dependence of microstructures and magnetic properties on B content was examined in Pr-Fe-B magnets produced by hot-rolling method. It was found that the microstructures of hot-rolled Pr-Fe-B alloy were remarkably changed with B content. The change of magnetic properties is related to this microstructural change. Excellent magnetic property is obtained in Pr15Fe79.5B5.5, which shows fine and network microstructures.

1. INTRODUCTION

A hot-rolled rare earth magnet is unique in terms of not only the crystal alignment induced by hot-rolling, but also the dependence of the magnetic properties on B content [1]. It is well known that the magnetic properties are influenced by the microstructures. In a previous paper, it was suggested that the optimum B content of hot-rolled Pr-Fe-B magnets is more than 5.0at%, which is the optimum B content of the hot-rolled Nd-Fe-B magnets [2].

In this study, B content dependence of microstructures and magnetic properties were examined for the Pr-Fe-B ternary alloy system. Moreover, optimum alloy composition is also discussed.

2. EXPERIMENTAL PROCEDURE

Alloy ingot of the nominal composition Pr15Fe85-xBx, with a range of x=4.0~8.0, was produced by induction melting under an argon gas atmosphere. Columnar microstructures were well developed in the ingots. The ingots were rolled at 1273K with a reduction of 76%. The samples were heat-treated at 1323K, and subsequently at 723K. Magnetic properties were measured by a DC B-H tracer with a maximum applied field of 26kOe, after magnetizing in a pulse magnetic field of 40kOe. The microstructures were examined by scanning electron microscopy.

3. RESULTS

3.1. Magnetic properties with B content

Figure 1 shows the relationship between energy product (BH)max and B content in samples after heat treatment. A maximum (BH)max value of 38.0MGOe is achieved at 5.5at%B. Figure 2 and Figure 3 show dependencies of Br and iHc on B content in these samples, respectively. With increasing B content, Br increases to its maximum value at around 5.5at%B, and then decreases gradually. iHc has a peak in the range of 4.0~5.5at%B and rapidly drops in the range of 6.0~8.0at%B. Consequently, the Pr15Fe79.5B5.5 alloy provides a superior magnetic property.

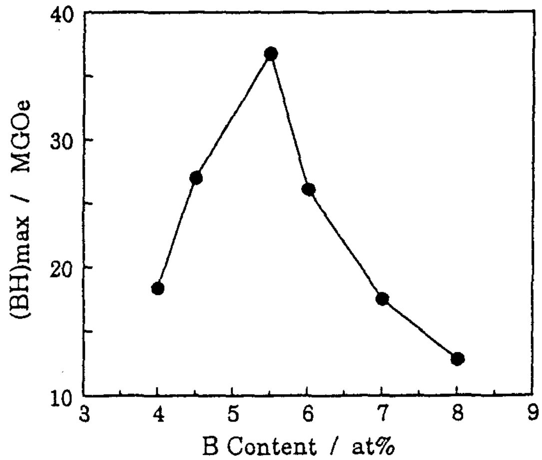

Figure 1. B content dependence of (BH)max after heat treatment.

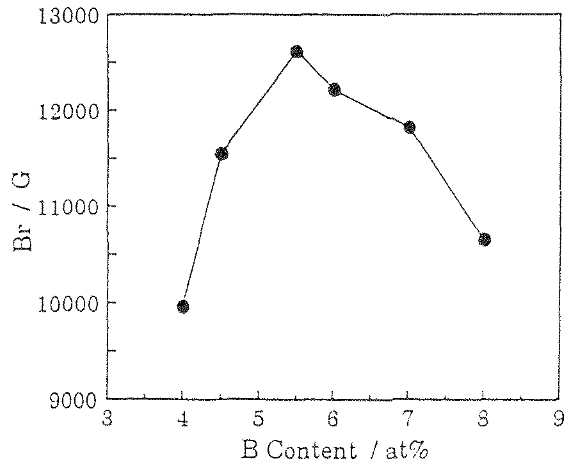

Figure 2. B content dependence of Br after heat treatment.

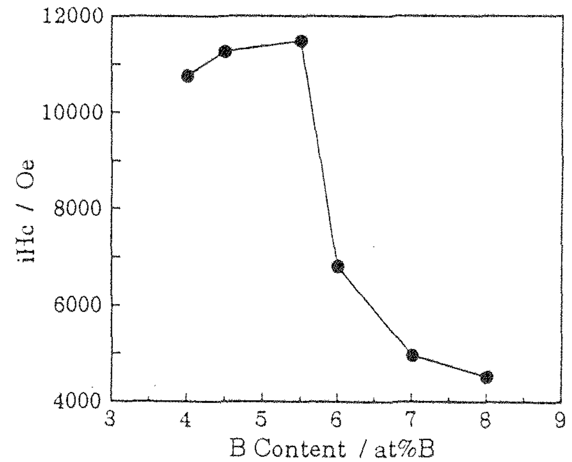

Figure 3. B content dependence of iHc after heat treatment.

3.2. Microstructures of magnets

Figure 4 shows the microstructures of the samples after heat treatment of 4.5~6.0 at%B. The microstructure of 4.5at%B consists of Pr2Fe17 (dark phase), Pr2Fe14B (gray phase) and Pr-rich phase (white phase). Grain size is comparatively fine, and each grain is separated by a grain boundary Pr-rich phase. In the sample of 5.5at%B, the microstructure does not contain the Pr2Fe17 phase, which is a magnetically impure phase. Moreover, the grain boundary phase forms a networklike structure, so that Pr2Fe14B grains are sufficiently separated from each other. In the sample of 6.0at%B, PrFe4B4 (dark phase), which is a magnetically impure phase, appears and a coarsening of the Pr2Fe14B matrix phase occurs. The grain separation through the grain boundary phase is not clearly observed as in 5.5at%B.

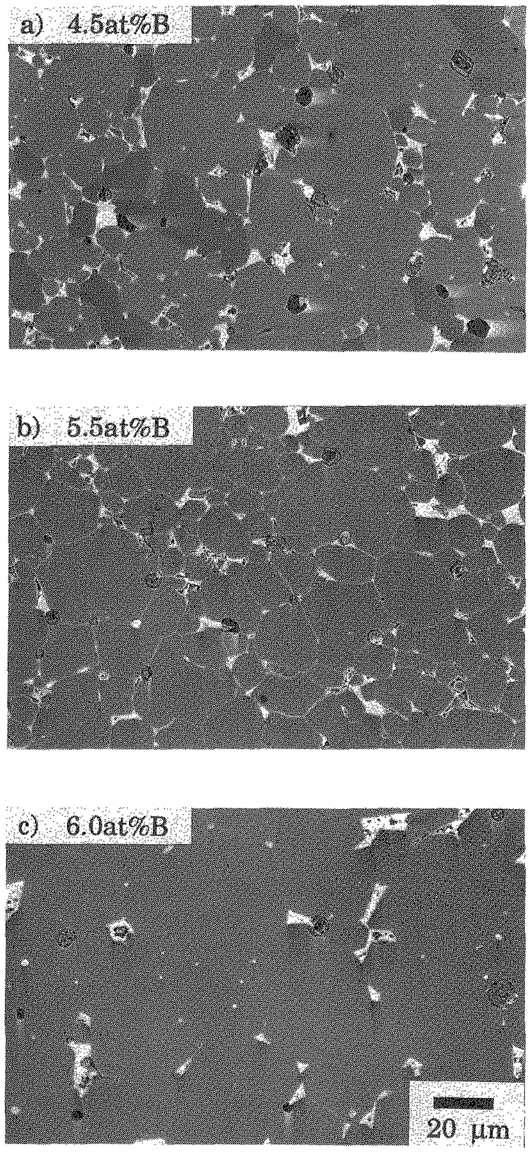

Figure 4. Microstructures of Pr15Fe85-xBx alloys after heat treatment.

3.3. Microstructure of ingots

Figure 5 shows the microstructures of the ingots with various B contents. The grain size and the morphology of the Pr2Fe14B phase of the sample of 8.0at%B are different from those of the samples of 4.0~7.0at%B. In a range of 4.0~7.0at%B, the microstructures consist of α-Fe (black phase), Pr2Fe14B (gray phase), Pr-rich phase (white phase), and Pr2Fe17 (dark phase, at 4.0at%B). The microstructures are characterized by a well-developed dendritic structure, whereas that of 8.0at%B contains Pr-rich phase and platelike coarsened Pr2Fe14B grains.

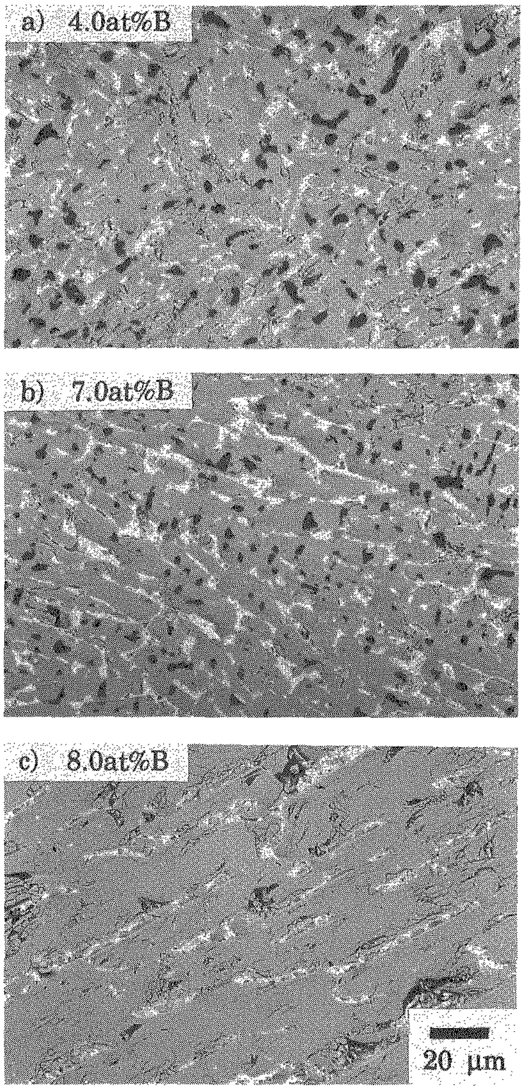

Figure 5. Microstructures of as-cast Pr15Fe85-xBx magnets.

4. DISCUSSION

As shown in Figure 2, Br exhibits the highest value in the sample of 5.5at%B, where the volume fraction of Pr2Fe14B is maximum in the examined B content range; that is, the Pr2Fe17 and PrFe4B4 phases, which are magnetically impure phases, are not observed in the microstructures. In addition, in view of the magnetic crystal alignment, the coarsened Pr2Fe14B grains prevent the development of magnetic crystal alignment during the hot-rolling [3]. The microstructure of ingot of 8.0at%B, as shown in Figure 5 contains platelike coarsened Pr2Fe14B grains, resulting in the poor Br shown in Figure 2. In the range of 4.0~7.0 at%B, however, it is observed that the Pr2Fe14B grain sizes in ingots are similar to each other. Therefore, there is no great difference in the extent of the magnetic crystal alignment through hot-rolling. As a result, the sample of 5.5at%B possesses the highest Br value.

Figure 3 and Figure 4 illustrate that samples of 4.5 and 5.5at%B, which have network structures, possess high iHc values. In the case of 6.0at%B, it is hard to observe the grain boundary phase, and to determine whether the magnetic isolation really occurs. In addition to this, grain size is another factor that affects iHc [4]. Figure 6 shows the distribution of grain size in 4.5~6.0at%B, which has rapid changes of iHc value with B

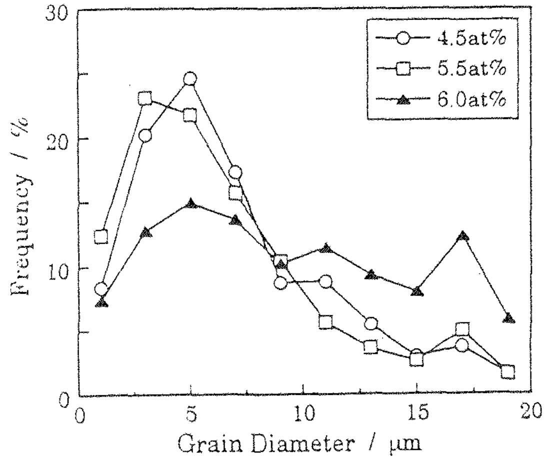

Figure 6. Distribution of grain size in the microstructures after heat treatment.

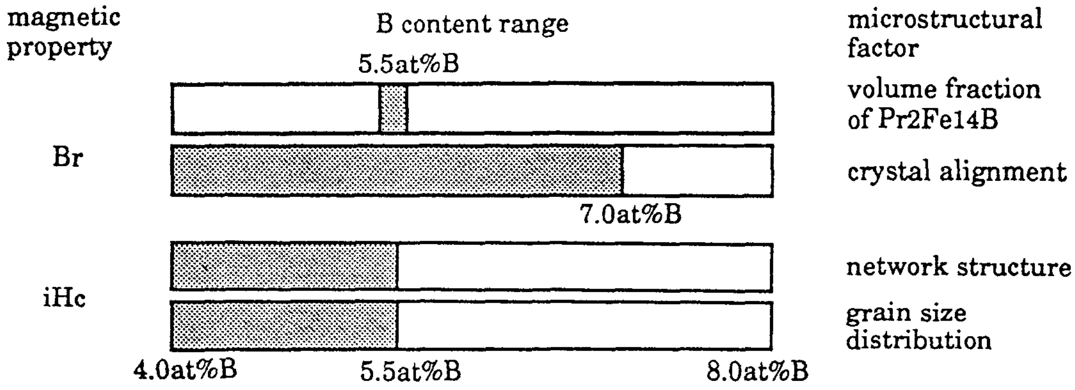

Figure 7. B content range of suitable microstructure for magnetic properties, [shaded box] represents desirable B content range for magnetic properties.

content. This figure shows that the grains are steeply distributed at diameters of around 5μm in 4.5~5.5at%B alloys as compared with 6.0at%B. Superior iHc value in the range of less than 5.5at%B is due to these sharply distributed fine grains. Judging from the above, a high iHc value could be achieved by a networklike structure or by a fine grain size distribution, whereas it would be widely dispersed in a 6.0 at%B alloy. Nevertheless, it is not certain which is the governing factor for affecting iHc.

Figure 7 shows the range of B content which realizes suitable microstructures for magnetic properties. Br shows the highest value if the magnetic crystal alignment is enhanced through the fine microstructure of an ingot, and if the maximum volume fraction of the Pr2Fe14B phase is obtained. iHc shows its maximum value if the microstructure exhibits both a network structure and a narrowly distributed microstructure in fine grain size. Hence, the optimum B content is around 5.5at%B.

5. CONCLUSION

The microstructures in hot-rolled Pr-Fe-B magnets are influenced by B content. A change of microstructure with B content results in changed magnetic properties. B content affects magnetic crystal alignment, which depends on the grain size at casting, and the volume fraction of the matrix phase, thus determining Br. The distribution of grain size and morphology of microstructure determine iHc. Most appropriate B content ranges for various microstructural factors are different from each other. The optimum B content for excellent magnetic properties exists in the narrow range around 5.5at%B. They are as follows: (BH)max=38MGOe, iHc=11.5kOe and Br=12.8kG.

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