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Neutron-absorption deformable boron-rich ferrous alloys

Shota Nakaidze, Vazha Garibashvili, Marina Antadze,* and Otar Tsagareishvili

Laboratory of Boron, Its Alloys and Compounds, F. Tavadze Institute of Metallurgy and Materials Science, Georgian Academy of Sciences, 15, Al. Kazbegi Ave., Tbilisi 380071, Georgia

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Abstract

The structure of the eutectic-type iron–boron alloys (up to 3.5 wt% B) crystallized at various velocities has been studied. It was established that due to temperature increase a coarse structure of the eutectic $Fe + Fe_2B$ transforms into a fine dendritic structure. High-temperature annealing leads to the destruction of columnar construction of the eutectic phase and boride dendrites subsequently transform into the inclusions of spherical shape. These processes are more active at high velocities leading to decrease of strength properties and increase of elasticity of the alloys. Such treatment makes possible hot repartition of the ingots from the alloys Fe + 3%B through their forging so that the ingots can be rolled into 3–5 mm thick platelets. The obtained product may serve as a material applicable for the preparation of neutron-absorption protective constructions.

Keywords: Neutron absorption; Eutectic; Bimetals; Explosion welding; Boron-rich alloy; Forging; Elasticity

1. Introduction

The threat of "nuclear terrorism" issues the challenge on application of neutron radiation protective materials in the constructions of, e.g. containers and storages intended for storage and transportation of radioactive sources. To these materials along with others are related iron–boron alloys. Main advantage of these alloys is that their fabrication is not labor intensive and do not require expensive initial materials for production. However, an efficiency of boron containing alloys is defined by a percentage of boron content. Concentration of boron in practically applied alloys is generally limited to 1 wt% B since at higher boron content the alloys become brittle and rigid.

As early as 1948 the Gottfild Scientific Center (USA) had much problems with preparation of iron–boron alloys with more than 2 wt% B at minimal content of other elements [1]. Deformability of the alloys was evaluated by forging and rolling of ingots. It was shown that boron-containing alloys were very brittle. Therefore, it was not easy to avoid formation of forging bends upon forging and impacts upon rolling.

In the constructions of protection system reactors there are usually in use boron-doped pearlitic steels. Boron concentration in these steels does not exceed 2 wt%, since it is assumed that at higher content of boron they become practically non-feasible [2]. Carbon content in iron–boron alloys must be minimal since it decreases deformability of boron-containing steels. Iron–boron alloys with low carbon content as well as high-boron stainless steels are rather brittle and cannot be used as construction materials due to low value of their impact viscosity.

2. Experiments and results

Iron–boron alloys containing up to 4 wt% B have been studied. It is known that iron–boron alloys are related to those of the eutectic type where the eutectic is formed with γ-Fe solid solution and hemi-boride Fe_2B. At the concentration of 3.83 wt% B the alloy contains 100% eutectic. Therefore, mechanical properties of the indicated alloys greatly depend on their eutectic structure.

Eutectic colony is a bi-crystal made of two phases—boride (Fe_2B) and solid solution of boron in γ-iron [3,4]. The colony has a shape of tetragonal prism, inherited

*Corresponding author. Fax: +995-32-253089.
E-mail address: mantadze@hotmail.com (M. Antadze).

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from crystals of the Fe_2B phase, which leads the processes of crystallization (Fig. 1).

Increase of the cooling velocity of the melts results in fracturing of the structure, increase of differentiation of eutectic components up to complete degeneration of colonial structure and formation of fine-grained conglomerates. Such changes of the structure lead to increase of hardness of iron–boron alloys.

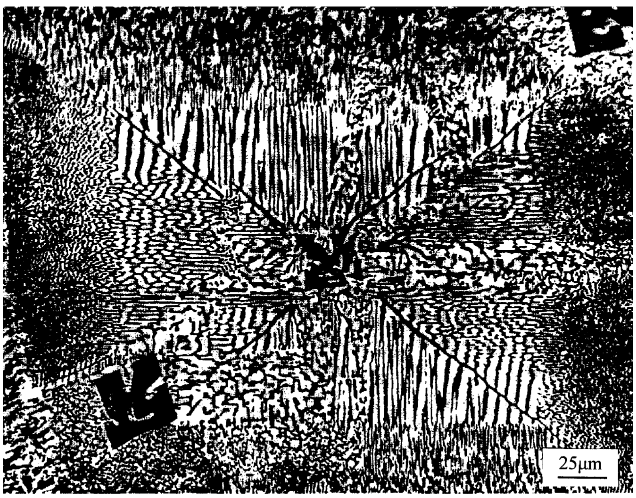

Fig. 1. Microstructure of an eutectic colony in Fe–B alloy.

Effect of heat treatment on the processes of spheroidization and coalescence of the eutectic boride constituent (3.4 wt% B) was studied on boron-containing alloys having close to eutectic structure. Eutectic structure in such case was not overshadowed with dendrites of solid solutions. For the comparison there were taken the alloys cooled with the rates of 1°C/min and 100°C/s. The ingots with pre-assigned cooling velocities were fabricated by pouring the material both in magnesite chill moulds and in thick-walled metal. The ingots were annealed for 24 h at 950°C. The structure of the alloys annealed at different time limits is shown in Fig. 2. The specimens for metallographic investigations were etched in sodium picrate at temperatures of 90–92°C.

Annealing for 6 h does not cause any significant changes to the structure of the alloy cooled at low velocity. At further annealing the destruction of boride colony branches begin. When annealing time approaches 18 h the destructed boride particles begin spheroidizing. Annealing for 24 h does not cause complete destruction to the eutectic skeleton structure.

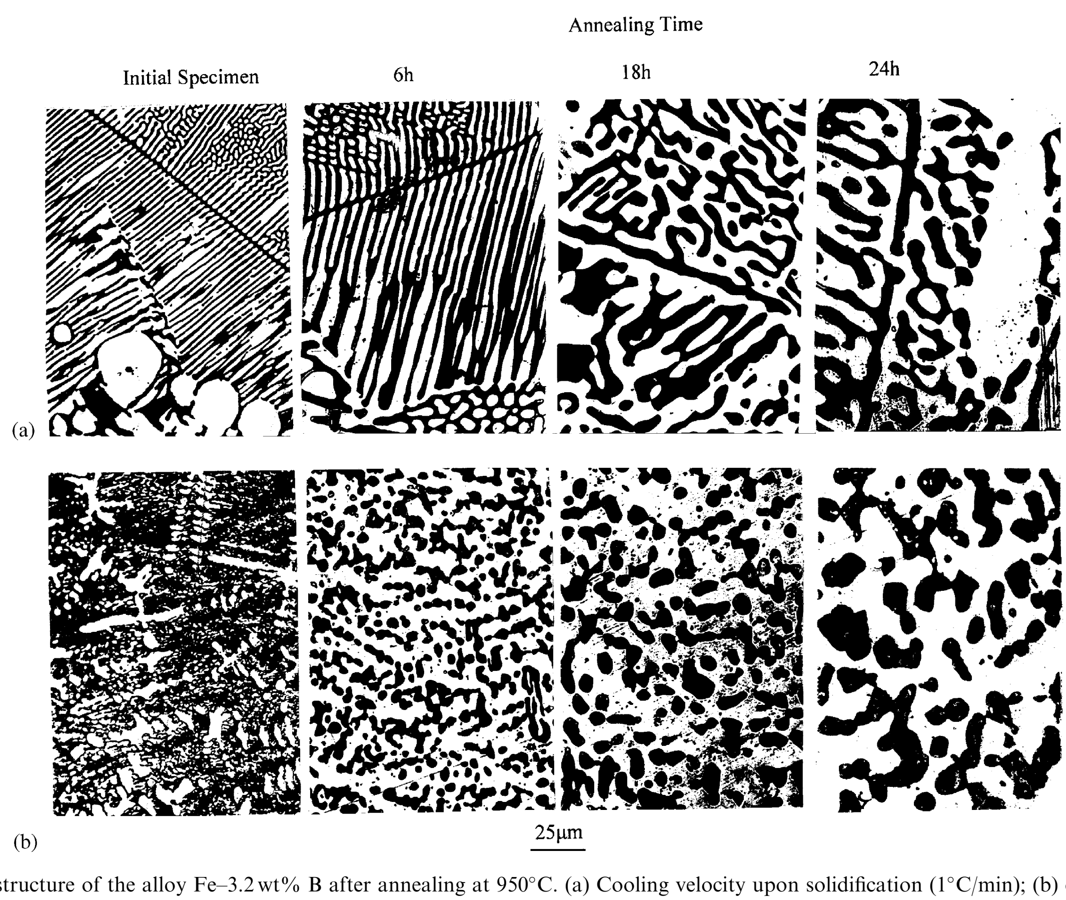

Fig. 2. Microstructure of the alloy Fe–3.2 wt% B after annealing at 950°C. (a) Cooling velocity upon solidification (1°C/min); (b) cooling velocity upon solidification (100°C/s).

Much sooner begins the process of destruction in rapidly crystallized alloy. After 6 h annealing boride constituents of the eutectic become completely spheroidized. Increase of the annealing time is conductive to the coalescence of boride particles, while annealing for 24 h transforms the structure of Fe–B eutectic into the matrix of solid solution with coarse inclusions of boride phase Fe_2B.

Increase of the crystallization velocity promotes to formation of rather imperfect dendrite-type structure, multiplies inter-phase defective areas contributing to acceleration of crushing and spheroidization processes.

Thus, broadening of defective areas in the structure of iron–boron alloys and increase of crystallization velocity leads to more rapid destruction and spheroidization of boride constituent of the eutectic. Boride inclusions begin to coalescence simultaneously with spheroidization through dissolution of small boride particles and coarsening of bigger ones, i.e. these processes can be attributed to a better-expressed curvature of small particles.

High initial differentiation of the eutectic promotes to acceleration of the coalescence processes. Therefore in the alloys, crystallized at higher velocities, coarsening of boride particles is more intensive.

Effect of the shape and dimensions of boride particles on hardness properties of Fe–B alloys is well exhibited at high-temperature annealing of these materials. For the comparison there were tested the alloys of similar concentration (3.2 wt% B) crystallized at different cooling rates (1°C/min; ~100°C/s).

Annealing time-dependent hardness of these alloys is shown in Fig. 3. Annealing of the specimens for 24 h at 950°C smoothly decreases hardness of the alloy cooled at low velocity, this probably being attributed to low rate of transformation of the eutectic boride skeleton. In the alloys with high cooling velocity (~100°C/s) the processes of destruction and spheroidization of boride particles proceed at much higher rate resulting in the changes of hardness characteristics. Annealing for the first 6 h leads to a strong decrease in hardness. At further increase of the annealing time where the processes of coalescence of boride particles are prevailing decrease of hardness characteristics occurs at lower velocities.

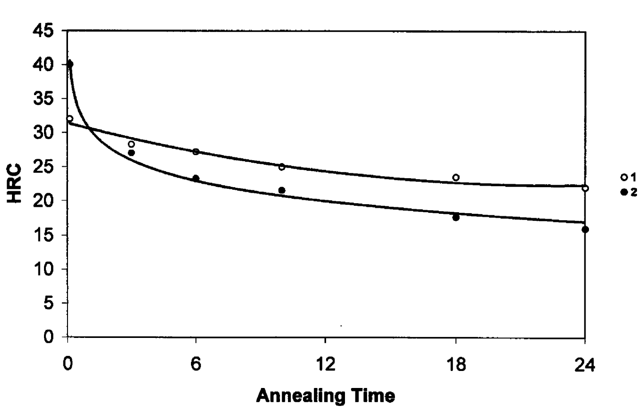

Fig. 3. Annealing time dependent hardness—in the alloy Fe–3.2% B annealing temperature—950°C. (1) Cooling velocity of the initial specimen—1°C/min. (2) Cooling velocity of the initial specimen ~100°C/s.

High-temperature annealing makes possible forging of rapidly quenched ingots (cast in iron moulds) and their further repartition in 5 mm thick sheets through hot rolling. However, a spectrum of mechanical characteristics of such sheets made of boron-rich alloys were not complete so the sheets could not be applied in neutron irradiation protecting constructions.

We think that one of the routes for solving the stated problem was fabrication of bimetallic or multi-layer materials made of combination of steel and Fe–B alloy layers using the technique of explosion welding (Fig. 4). In such compositions where high strength of junction of different metals is ensured, the required mechanical properties may successfully be combined with those of neutron irradiation protective materials. Considerably low cost of the applied materials as well as simplicity of the technology of fabrication bimetals by explosion welding makes these heterogeneous materials economically advisable.

Cohesion strength between the layers in bimetallic materials obtained by explosion welding is mainly defined by a character of junction zone, in particular, by melted points occurring at some local areas due to significant increase of temperature at surface layers of the conjugated metals through impulsive mechanical interaction and further crystallization [5]. Fig. 5 shows microstructure of transition layer of the bimetallic specimen (steel + Fe–B alloy) after the explosion welding and annealing for 3 h at ~1000°C. Specimens were etched with 3% HNO_3 solution. Probably the transition layers by welding of Fe–B alloys to the construction steels have been formed mainly due to flashing of the component with the lowest melting point, in our case the component being Fe–Fe_2B eutectic. Crystallization of these alloys in extreme conditions leads to the formation

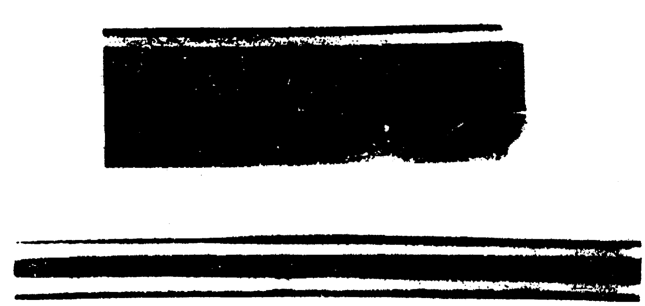

Fig. 4. Construction steel layered with Fe–B alloy (specimen made by the explosion welding technique).

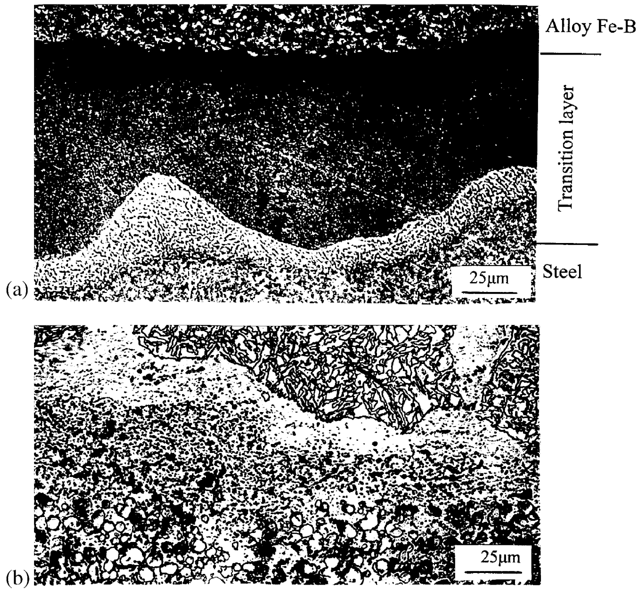

Fig. 5. Microstructure of transition layer of the bimetallic specimen (steel + Fe–B alloy).

of structural constructions, which are similar to those being formed upon crystallization of the eutectic structure at high velocities. Hence, the structure and properties of the junction zones in the obtained material may be changed in coordination with the specified pre-assigned purposes.

3. Conclusion

By maintaining of the necessary crystallization velocity upon casting and further high-temperature annealing of Fe–B alloys with boron content up to eutectic (3.83 wt% B) it is possible to achieve significant structural changes in the obtained castings. The special treatment processes improve the deformability of the specimens. The obtained hot-rolled sheets can be successfully welded with the construction steel by the explosion technique. Physical–mechanical properties of the obtained heterogeneous layered materials can be specified.

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