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Kinetic analysis of MgB_2 layer formation in advanced internal magnesium infiltration (AIMI) processed MgB_2 wires

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Abstract

Significantly enhanced critical current density (J_c) for MgB_2 superconducting wires can be obtained following the advanced internal Mg infiltration (AIMI) route. But unless suitable precautions are taken, the AIMI-processed MgB_2 wires will exhibit incomplete MgB_2 layer formation, i.e. reduced superconductor core size and hence suppressed current-carrying capability. Microstructural characterization of AIMI MgB_2 wires before and after the heat treatment reveals that the reaction mechanism changes from a “Mg infiltration-reaction” at the beginning of the heat treatment to a “Mg diffusion-reaction” once a dense MgB_2 layer is formed. A drastic drop in the Mg transport rate from infiltration to diffusion causes the termination of the MgB_2 core growth. To quantify this process, a two-stage kinetic model is built to describe the MgB_2 layer formation and growth. The derived kinetic model and the associated experimental observations indicate that fully reacted AIMI-processed MgB_2 wires can be achieved following the optimization of B particle size, B powder packing density, MgB_2 reaction activation energy and its response to the additions of dopants.

Keywords

Magnesium diboride; AIMI; infiltration; kinetics; electron microscopy

1. Introduction

MgB_2 with its medium critical temperature ($T_c = 39$ K), inexpensive raw materials and round multifilament form [1] is very suitable for practical superconducting wires. Over the past decade, the performance of MgB_2 has been remarkably improved [2–6], which resulted in commercially available, long-length MgB_2 superconducting wires [7, 8] used in magnetic resonance imagers [9] and wind turbine generators [10]. However, the conventional MgB_2 wires, fabricated by the powder-in-tube (PIT) method, generally suffer from “high porosity and weak intergranular connectivity” [11, 12]. As a result, it is extremely difficult to achieve the critical current density (J_c) needed for applications that require working temperatures around 20 K and magnetic fields of 5–10 T.

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Recent research has demonstrated that the infiltration process is effective in producing dense and well-connected MgB_2 with J_{cs} of over $1.0 \times 10^5 \text{ A cm}^{-2}$ at 4.2 K and 10 T [13–16], much higher than those of typical PIT MgB_2 conductors. In preparation for the infiltration process, a Mg rod placed along the axis of a metal tube is surrounded by B powder. During heat treatment the Mg melts and infiltrates into the B preform. Because of the volume expansion that accompanies the $\text{B} \rightarrow \text{MgB}_2$ reaction, voids in the initial B preform are entirely filled. Consequently, a fully dense cylinder of MgB_2 replaces the initial B preform. Although this method produces high-quality MgB_2 with superior layer- J_{c} , it has been found that the MgB_2 layer growth stops shortly after the onset of the heat treatment, leaving an unreacted B shell, and a less-than-optimal engineering current density J_{e} (i.e. critical current over whole strand area) [14, 17]. Recent advances by our group have led to an empirical understanding of the limiting layer thickness effect, and have allowed us to modify wire geometry/design, precursor choice, and heat treatment conditions to minimize this effect [18]. Our advanced internal Mg infiltration (AIMI) wire design achieves complete reaction of an infiltration based composite, resulting in not only a high layer- J_{c} but also an enlarged MgB_2 cross-sectional area hence increased MgB_2 fill factor and J_{e} . Nonetheless, our knowledge of the mechanism of MgB_2 layer formation was far from adequate to overcome the experimental difficulties encountered in the development of AIMI wires. For example, while C doping proved to be the most effective way to enhance the layer- J_{c} , it suppressed the MgB_2 layer growth at the same time. So a heavily C-doped AIMI wire ended up with a poorly reacted conductor with high layer- J_{c} but low MgB_2 fill factor and low J_{e} [19]. Therefore, to further develop the infiltration-processed MgB_2 wire it became necessary to investigate the kinetics of the $\text{B} \rightarrow \text{MgB}_2$ formation process during the heat treatment and to identify the variables that control MgB_2 formation.

The microstructural evolution in the AIMI-processed MgB_2 wires before and after the heat treatment was examined by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The microscopic observations showed that a dense MgB_2 layer is formed in the place of initial B precursor layer shortly after the onset of heat treatment. The Mg transport mechanism changes from reactive infiltration through B at the beginning, to diffusion through MgB_2 into the remaining unreacted B once the initial layer is formed—a much slower process. A two-stage model has been developed to describe this kinetic process, one that perfectly explains the experimental observations and provides suggestions for future AIMI wire development.

2. Experimental

The microstructural evolution of a previously reported AIMI-processed MgB_2 wire [18] was characterized. The wire was 0.83 mm in outer diameter, consisted of a Mg rod positioned along the axis of a B-filled double tube of Nb (the chemical barrier) and Monel® (the hard outer sheath). Nano-sized B powders from Specialty Materials Inc, pre-doped with 2 mol. % C enabled an enhancement of the pinning strength and an increase in the upper critical field $B_{\text{c}2}$ [5, 20]. A segment of the filled-and-drawn wire was encapsulated in a quartz tube under Ar, and reacted at 675 °C for 1 h at which point, according to previous research [18], we expected the MgB_2 layer growth to stop. For comparison purposes, another segment removed from the as-drawn wire prior to the heat treatment was cold pressed by a home-

made pressing machine under a horizontal load of 32.5 kN and a vertical load of 68.5 kN, deforming its cross-section from circular (0.83 mm diameter) to rectangular ($0.94 \times 0.65 \text{ mm}^2$).

Microstructures were studied by a FEI Sirion FEG SEM, and a FEI/Philips CM-200T TEM with LaB_6 cathode. The TEM samples were prepared by a FEI Helios NanoLab 600 DualDeam focused ion beam (FIB) equipment.

3. Results and Discussion

3.1. Microstructural evolution

The microstructural evolution in the AIMI-processed MgB_2 wires before and after the heat treatment has been investigated using SEM and TEM. Fig. 1(a) shows the fracture cross-section of the unreacted AIMI wire. The Mg, located in the wire center, is surrounded by an annular layer of B. Once heated above 650°C , the Mg melts and reactively infiltrates the B preform, transforming B into MgB_2 . Fig. 1(b) shows the B precursor layer as being composed of randomly-packed B spheres whose sizes are 10–120 nm and 60 nm on average [21]. According to Scott *et al.* [22], the maximum packing density for randomly packed spheres is around 64%. So as seen in Fig. 1(b) a large quantity of dispersed nano-sized voids exists amid the B particles and acts as capillary network for Mg infiltration. The formation of MgB_2 quickly consumes the Mg leaving behind a central hole. Fig. 2(a) and Fig. 2(b) show the cylindrical core that replaces the B preform during heat treatment at 675°C for 1 h. Detailed SEM analysis reveals the microstructural change along the cross-sectional radius of the cylinder, from a dense layer (Fig. 2(c)) to a transition region (Fig. 2(d)) and eventually to a porous layer (Fig. 2(e)). The dense layer located at the very inner side contains almost no porosity (Fig. 2(c)). Energy dispersive spectroscopy (EDS) analysis identifies the composition of this layer as MgB_2 , so we also refer it as “ MgB_2 layer”. It is this region in the wire that provides the superconductivity. Outside the MgB_2 layer is a transition region as well as a surrounding porous layer. The porous layer itself is enclosed, as shown in Fig. 2(e), by an outer region, in this case mainly composed of nano-sized B spheres (indicating incomplete MgB_2 formation) positioned close to the outer surface of the cylinder. This last layer, close to the outer cylinder is the “unreacted B layer”. In addition, the “transition region” between the “unreacted B layer” and the “ MgB_2 layer”, indicates a microstructural evolution from the porous B-rich structure to dense MgB_2 . As displayed in Fig. 2(d), dense bulk phases are gradually formed when B particles react with Mg and coalesce with each other. However, given its weak connectivity, this transition region is unable to contribute significantly to the transport J_c .

The MgB_2 layer and the partially-reacted transition region were also examined by TEM. Fig. 3(a) shows the microstructure in “ MgB_2 layer”, whose platelet-shaped grains are about 20–40 nm in width and 100–200 nm in length. In contrast, not only MgB_2 platelets but also unreacted B spheres, as well as voids, are observed in the transition region (Fig. 3(b)). This feature, similar to Fig. 2(d), demonstrates the microstructural transformation from B to MgB_2 .

3.2. Kinetic analysis of MgB₂ layer formation in AIMI wires

Microstructural analysis provides a useful starting point for analyzing the mechanism of MgB₂ layer growth in AIMI wires. Fig. 4 schematically depicts it as a two-stage process. In Stage-I, heat treatment of the AIMI-processed precursor wire leaves a Mg-depleted core surrounded by a thin cylinder of almost fully dense MgB₂ produced by the initial rapid infiltration of liquid Mg. Because of the abundance of Mg, Stage-I is a “reaction-controlled” process. In Stage-II, reaction of the B remaining outside this cylinder requires the diffusion of Mg through the dense MgB₂ inner layer. Due to a dearth of Mg, Stage-II proceeds very slowly and is mainly “diffusion-controlled”. In what follows a kinetic model is developed to describe the two-stage process.

3.2.1. Stage-I, dense MgB₂ layer formation—Stage-I is the reactive infiltration of liquid Mg into a porous B compact. The porous B provides a capillary network to encourage liquid Mg infiltration. As infiltration occurs, Mg is reacting with B at the same time, forming MgB₂. Since the molar volume of MgB₂ (17.46 cm³ mol⁻¹) is three times larger than that of B (4.59 cm³ mol⁻¹) [12], the interstitial voids between the initial B particles are gradually filled as liquid Mg continues to infiltrate. The depth of the infiltration grows with time, and during this time the Mg is in reaction with B powder all along the infiltration path. Eventually an MgB₂ layer with almost 100% density is formed starting close to the surface of the prior Mg rod and extending all along the infiltration path. In short, during reactive infiltration the particles expand and eventually block the paths to further infiltration, resulting after time t_0 in a dense MgB₂ layer of thickness x_0 . There are two components to t_0 . First there is the time $t_p = x_p^2/D_p$ needed to allow Mg to fully diffuse into the individual B particles of characteristic size x_p , where D_p is the diffusion coefficient for Mg in B. To be added to this is the time t_{form} needed to complete the $\text{Mg} + \text{B} \rightarrow \text{MgB}_2$ reaction.

In calculating t_{form} we start by taking X as the powder packing fraction in the B preform. Then according to the stereology [23], for randomly packed powders, the area fraction of B occupying the Mg/B interface is also X . The value of X typically varies around 64% for systems composed of randomly close-packed spheres, such as B powders in the as-drawn MgB₂ precursor wire. According to previous analysis [12, 18], a complete reaction of B powders with $X \sim 64\%$ happens to result in the formation of fully dense MgB₂. Therefore, in order for the completion of Stage-I, B powders close to the prior Mg/B interface have to be totally reacted into MgB₂. If A_{SC} is the area of the Mg/B interface then the area of precursor B powder covering the interface is $A_{\text{SC}} X$. Thus the amount of B along the Mg/B interface is

$$n_{\text{B}} = \frac{A_{\text{SC}} X}{N_{\text{B}}} \quad (\text{mol}) \quad (1)$$

where N_{B} is the molar area for B ($2.33 \times 10^4 \text{ m}^2 \text{ mol}^{-1}$). Similar to molar volume in the three-dimensional system, the concept of molar area is introduced to quantify the concentration of B along the two-dimensional interface [24]. An estimation of N_{B} is provided in the appendix.

MgB₂ reaction is completed along the Mg/B interface in time t_{form} at an MgB₂ formation rate form MB S

$$J_{\text{form}} = k_{\text{MB}} C_{\text{S}} \quad (\text{mol m}^{-2} \text{s}^{-1}) \quad (2)$$

where C_{S} is the concentration of Mg at the interface and k_{MB} is the rate constant (m s^{-1}) for the chemical reaction $\text{Mg} + \text{B} \rightarrow \text{MgB}_2$. According to chemical kinetics, k_{MB} only depends on temperature and reaction activation energy such that $k_{\text{MB}} = k_{\text{MB}}^* \exp(Q_{\text{MB}}/RT)$, in which k_{MB}^* is the reaction rate constant at standard conditions and Q_{MB} is the activation energy for MgB₂ formation. The amount of MgB₂ formed at the Mg/B interface is therefore

$$n_{\text{B}} = J_{\text{form}} \cdot t_{\text{form}} \cdot A_{\text{SC}} \quad (\text{mol}) \quad (3)$$

Upon combining Equations 1, 2 and 3 we find

$$t_{\text{form}} = \frac{X}{k_{\text{MB}} C_{\text{S}} N_{\text{B}}} \quad (\text{s}) \quad (4)$$

Thus the total time for Stage-I is

$$t_0 = t_{\text{form}} + t_{\text{p}} = \frac{X}{k_{\text{MB}} C_{\text{S}} N_{\text{B}}} + \frac{x_{\text{p}}^2}{D_{\text{p}}} \quad (\text{s}) \quad (5)$$

According to the Washburn model for liquid metal infiltration into porous media [25], the infiltration depth of liquid Mg into B is

$$x_0 = \left(\frac{r \gamma \cos \theta}{2\eta} \right)^{1/2} (t_0)^{1/2} \quad (\text{m}) \quad (6)$$

where r , γ , θ , and η are effective pore radius, surface tension, wetting angle between liquid Mg and B, and viscosity, respectively. It is noted that the Washburn model assumes the capillary effect plays the dominant role during the infiltration process. There are a few other factors which possibly contribute to liquid Mg infiltration into B, such as the gravity of liquid Mg, the pressure of the surrounding space above the liquid Mg [25] and the negative pressure created due to the volume shrinkage during MgB₂ formation [15]. Thus, it may require a slight modification in Equation 6 when considering these factors [25]. But x_0 should still follow the general relationship of the above expression.

Combining Equations 5 and 6 we find an expression for the MgB₂ layer thickness, x_0 , when Stage-I is accomplished

$$x_0 = \left(\frac{r\gamma\cos\theta}{2\eta} \right)^{1/2} \left(\frac{X}{k_{MB}C_S N_B} + \frac{x_p^2}{D_p} \right)^{1/2}. \quad (m) \quad (7)$$

Equation 7 shows that x_0 is affected by many parameters including the preform packing density (X), the average pore size (r), the $Mg+B \rightarrow MgB_2$ reaction rate (k_{MB}) and, very importantly, the B particle size (x_p). The first term of Equation 5 represents a situation where just the intrinsic $Mg+B$ reaction (very local) is limiting, the second where the diffusion into the B particle is the controlling factor for setting the time for the infiltration process. In practice, as demonstrated in our later discussion, this latter term is dominant, such that Equation 7 can be approximated with the second term only.

3.2.2. Stage-II, prolonged heat treatment—After the completion of Stage-I all capillaries for infiltration are blocked. Further reaction requires Mg to diffuse through a dense MgB_2 layer, a process of similar to the “Si thermal oxidation process” discussed by Deal and Grove [26]. With a Mg concentration at the initial Mg/B interface of C_S dropping to C_i at the MgB_2/B interface the diffusion flux through the dense layer of thickness x_0 is

$$J_{diff} = \frac{D_{II}(C_S - C_i)}{x_0} \quad (\text{mol m}^{-2} \text{s}^{-1}) \quad (8)$$

in which D_{II} is the diffusion coefficient for Mg through MgB_2 .

This is equal to the rate of MgB_2 formation starting at the MgB_2/B interface:

$$J_{form} = k_{MB} C_i. \quad (\text{mol m}^{-2} \text{s}^{-1}) \quad (9)$$

Since J_{diff} must equal J_{form} for mass equilibrium, we can eliminate C_i between Equations

$$J_{diff} = \frac{D_{II} k_{MB} C_S}{k_{MB} x_0 + D_{II}}. \quad (\text{mol m}^{-2} \text{s}^{-1}) \quad (10)$$

After inserting N_v (mol m^{-3}), the amount of Mg needed to produce unit volume of MgB_2 , the layer growth rate can be written

$$\frac{dx_0}{dt} = \frac{J_{diff}}{N_v} = \frac{D_{II} k_{MB}}{k_{MB} x_0 + D_{II}} \cdot \frac{C_S}{N_v}. \quad (\text{m s}^{-1}) \quad (11)$$

Then since Stage-II is a diffusion-controlled process, such that $k_{MB} x_0 \gg D_{II}$, Equation 11 reduces to

$$\frac{dx_0}{dt} = \frac{D_{II} C_S}{N_v} \cdot \frac{1}{x_0} \quad (\text{m s}^{-1}) \quad (12)$$

the solution to which is

$$x_0^2 = \frac{2D_{II}C_S}{N_V} \cdot t + \text{const.} \quad (\text{m}^2) \quad (13)$$

The constant in Equation 13 can be evaluated by considering as a starting point for Stage-II the terminal conditions for Stage-I, viz x_0 and t_0 , which for the present purpose we now write as x_0^* and t_0^* . After doing so we find

$$x_0^2 = \frac{2D_{II}C_S}{N_V} \cdot (t - t_0^*) + (x_0^*)^2. \quad (\text{m}^2) \quad (14)$$

3.3. Discussion

In order to compare the Stage-I and Stage-II layer thicknesses we need to insert numerical values into Equation 14: (i) the diffusion coefficient $D_{II} = 10^{-17} \text{ m}^2 \text{ s}^{-1}$ [27], (ii) the molar volume of liquid Mg, $C_S = 6.52 \times 10^4 \text{ mol m}^{-3}$, and (iii) the amount of Mg per m^3 of MgB_2 , $N_V = 5.73 \times 10^4 \text{ mol m}^{-3}$. Equation 14 then becomes

$$x_0^2 = 2.28 \times 10^{-5} (t - t_0^*) + (x_0^*)^2. \quad (\mu\text{m}^2) \quad (15)$$

According to our previous experimental results [18], an AIMI wire acquired a Stage-I reaction layer thickness (x_0^*) of 50 μm after 60 min at 675 °C. Suppose the heat treatment is extended into Stage-II for a further time, $t - t_0^* = 60 \text{ min}$. After substituting these numbers into Equation 15 we find the new layer thickness, x_0 , to be equal to 50.0008 μm , which represents no significant increase in x_0^* beyond the Stage-I value, in reasonable agreement with our previous report [18] and results by other groups [14]. In other words, the very small diffusivity of Mg through the dense Stage-I layer prevents a large additional increase in layer thickness. Only grain-boundary-induced increases in D_{II} would lead to significant amounts of Stage-II MgB_2 . As a consequence, the MgB_2 layer thickness for AIMI wires is nearly equal to the thickness of the MgB_2 layer formed in Stage-I.

As shown in Equation 5, the time for completing Stage-I is the time needed for Mg to diffuse into the B particles, t_p , plus the time for MgB_2 formation, t_{form} . The $\text{Mg} + \text{B} \rightarrow \text{MgB}_2$ reaction rate k_{MB} at 675 °C is estimated to be about $10^{-10} \text{ m s}^{-1}$ [27, 28]. Hence t_{form} , calculated from Equation 4 using $X = 0.64$, $N_B = 2.33 \times 10^4 \text{ m}^2 \text{ mol}^{-1}$, and $C_S = 6.52 \times 10^4 \text{ mol m}^{-3}$, amounts to 5 s, a fairly short time. On the other hand the time for the Mg to diffuse into the largest B particles (i.e. $x_p = 120 \text{ nm}$ and $D_p = 8 \times 10^{-18} \text{ m}^2 \text{ s}^{-1}$) [29], t_p , is about 48 min. This is much longer than the formation time, t_{form} , and indeed close to a Stage-I experimental result [18]. The comparison between t_{form} and t_p indicates that the time for Stage-I is dominated by t_p —that required for Mg to fully diffuse into B particles. By manipulating the B particle size or Mg diffusion rate into B, it is possible to extend the time for dense MgB_2 layer formation, thus broadening the thickness of MgB_2 layer. In this way, Giunchi *et al.* were able to produce large dense MgB_2 objects (“manufacts”) from crystalline B ground to sizes of 40–180 μm albeit at the expense of $J_c(B)$ which decreased as x_p increased from 1 $\mu\text{m} \rightarrow 40 \mu\text{m} \rightarrow 100 \mu\text{m} \rightarrow 180 \mu\text{m}$ [30, 31].

Besides reaction time, other factors like average pore radius also affect the MgB_2 layer thickness in AIMI wires. Large pores usually provide wide capillaries, thus facilitating the infiltration. Fig. 5 demonstrates the effect of pressing on the MgB_2 layer thickness. Pressing densifies the B preform, reduces the pore size within the precursor layer, and suppresses the infiltration during MgB_2 layer formation. As shown in Fig. 5, the MgB_2 layer thickness drops from 30–40 μm for the unpressed AIMI wire to less than 15 μm for the pressed specimen. According to Equation 7, the thickness x_0 also involves the surface tension and viscosity of liquid Mg, and the wetting angle between liquid Mg and B. At 675 $^\circ\text{C}$, the surface tension of liquid Mg is about 0.563 N m^{-1} , and its viscosity is 1.119–1.147 $\text{mPa}\cdot\text{s}$ [32]. It is reported that liquid Mg has very poor wettability on nanosized commercial B [31]. But unfortunately, no record has been found regarding the numerical value of the Mg-B wetting angle. Once the wetting angle becomes known, we will be able to predict x_0^* based on the kinetic model above. In addition, according to Equation 7, we can see that efforts to improve the wettability or Mg surface tension are likely to contribute to an increase in the MgB_2 layer thickness – a possible direction for future wire development.

Last to be discussed is the effect of C dopant concentration. In a recent paper we have reported on the suppression of the MgB_2 layer thickness as a result of C doping [19]. DeFouw *et al.* [27] studied the MgB_2 reaction activation energies, Q_{MB} , for various types of B. For undoped plasma-synthesized boron Q_{MB} is 108 kJ mol^{-1} , and for C-doped plasma-synthesized B it is 70 kJ mol^{-1} . So at a given reaction temperature, C-doped AIMI wires which react faster than undoped ones (i.e. larger k_{MB}) exhibit a shorter time for dense MgB_2 layer formation. Furthermore C doping generates a higher density of defects in B powders [5], so Mg diffusion into B speeds up and t_p decreases accordingly. Both effects combine to reduce the MgB_2 layer thickness for C-doped AIMI wires.

4. Conclusions

A careful SEM and TEM study of microstructural evolution indicates a two-stage mechanism for MgB_2 layer formation in AIMI-processed MgB_2 wires. Our kinetic model and the accompanying discussions reveal that the final MgB_2 layer thickness is mainly governed by the thickness of MgB_2 formed during the first stage. The final thickness of the MgB_2 reaction layer is shown to depend not only on reaction time but also on B particle size, pore size in the preform, wetting angle and reaction activation. In general, the reaction layer will increase rapidly until it reaches a depth x_0 , after which grows very slowly, such that x_0 can be defined as a “saturation reaction depth”. It can be shown that x_0 is linearly dependent on B powder size, proportional to the square root of the radius of the porosity, and inversely dependent on the reaction rate of the local MgB_2 formation reaction. The kinetic analysis together with the expression for MgB_2 layer thickness provide valuable tools for further optimization of the already high-performance AIMI-processed MgB_2 superconductors.

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Appendix

Conversion of 3-dimensional molar volume of B into 2-dimensional molar area within a plane (i.e. surface or interface): Assume isotropic, homogeneously distributed unit cells inside of a crystal. The volume for a B unit cell can be estimated by the 3-dimensional molar volume of B ($4.59 \text{ cm}^3 \text{ mol}^{-1}$) divided by the Avogadro's number ($6.02 \times 10^{23} \text{ mol}^{-1}$). So the volume for a B unit cell is $7.6 \times 10^{-24} \text{ cm}^3$. Thus, the cross-sectional area for this unit cell is about $3.87 \times 10^{-16} \text{ cm}^2$, resulting in a planar density of MgB₂ unit cells equal to $2.58 \times 10^{15} \text{ cm}^{-2}$. Dividing Avogadro's number by the planar density, we get an estimation of MgB₂ molar area to be $2.33 \times 10^8 \text{ cm}^2 \text{ mol}^{-1}$, i.e. $2.33 \times 10^4 \text{ m}^2 \text{ mol}^{-1}$.

Fig. 1.

a) Fractural cross-sectional SEM image of the unreacted AIMI wire. The Monel® sheath is etched away by nitric acid before observation. b) Enlarged SEM picture of the porous B preform which consists of nano-sized B particles and interstitial voids.

Fig. 2.
 a,b) Fractural cross-sectional SEM images of the AIMI wire heat treated at 675 °C for 1 h.
 c–e) SEM images of the dense MgB_2 layer, transition region and B-rich layer respectively.

Fig. 3.

a) Bright field TEM image of a dense MgB_2 layer. (insert: selective area diffraction image taken from the dense layer identifies the MgB_2 phase. b) TEM image of the transition region consisting of MgB_2 platelet grains, B spheres and voids.

Fig. 4. Schematic picture of the two-stage formation mechanism of the MgB_2 layer in AIMI – processed MgB_2 wires.

Fig. 5.

Back-scattered SEM images of a) an unpressed AIMI wire and b) a pressed AIMI wire. The image contrast is adjusted to clearly show the MgB₂ layer and B-rich layer.