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INFLUENCE OF SYNTHESIS METHODS ON THE STRUCTURE AND PROPERTIES OF ALUMINUM BORIDES

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Abstract
The paper presents a comparative analysis of the influence of the principal synthesis methods on the structure and properties of aluminum borides. Conventional high-temperature synthesis, mechanical alloying, self-propagating high-temperature synthesis, plasma synthesis, molecular beam epitaxy, and electron-beam processing are analyzed with respect to their effect on phase formation, microstructure, structural homogeneity, and defect evolution. The relationship between synthesis conditions and the mechanical, thermal, electrical, and chemical properties of aluminum borides is discussed. The comparative evaluation demonstrates that the selection of an appropriate synthesis route and optimization of the processing parameters are essential for controlling the structure and achieving the desired functional properties of Al–B materials.

Keywords: aluminum borides; AlB_2; AlB_{12}; synthesis methods; microstructure; properties; electron-beam modification.

INTRODUCTION

The development of modern engineering materials is closely related to the possibility of purposefully controlling their properties through the selection of an appropriate production technology. In materials science, this relationship is described by the "process–structure–properties" concept, according to which the processing parameters determine the phase formation, microstructure, and performance characteristics of the material [1,2].

Aluminum borides are a promising class of boron-containing materials characterized by low density, high hardness, good chemical resistance, and high thermal stability. The Al–B system continues to attract scientific interest due to the possibility of the existence of new stoichiometric phases and specific electronic properties, which expand the prospects for future functional applications [12]. The properties of aluminum borides depend to a significant extent on the synthesis technology used, which determines the phase composition, microstructure, and structural homogeneity [3–6].

Among the modern technologies, mechanical alloying, self-propagating high-temperature synthesis, plasma synthesis, molecular beam epitaxy, and electron-beam modification occupy a special place. They provide effective control over phase formation and microstructure development [6–8]. Electron-beam modification is of particular interest, which, due to its high energy density, localized impact, and processing in vacuum, is considered a promising method for producing boride surface layers. Although its application to the Al–B system is still limited, the results obtained for other metal–boron systems demonstrate the significant potential of the technology [7–10].

The aim of the present review is to analyze the influence of different synthesis methods on the structure and properties of

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aluminum borides by tracing the relationship between processing parameters, phase formation, microstructure, and performance characteristics, with special emphasis on the possibilities of electron-beam modification.

EXPOSITION

1. Influence of Synthesis Methods on the Structure of Aluminum Borides

The structure of aluminum borides is formed because of the interaction between aluminum and boron under conditions determined by temperature, processing time, energy input, heating and cooling rates, and the degree of mechanical activation of the starting components. Each synthesis method creates specific kinetic conditions for diffusion processes and crystallization and therefore has a direct influence on the phase composition, crystal size, morphology, defect state, and structural homogeneity of the obtained materials [3–8].

1.1. Influence of the Synthesis Method on Phase Formation

Phase formation in the Al–B system is determined by temperature, processing time, the ratio between aluminum and boron, and the degree of contact between the reacting components, which determine the diffusion rate and the sequence of formation of the boride phases [3–6].

Mechanical alloying increases the reactivity of powder mixtures through intensive plastic deformation and mechanical activation, which accelerates diffusion processes and allows the synthesis of AlB_2 at lower temperatures compared to conventional solid-state synthesis [3]. In high-temperature synthesis, phase formation is controlled mainly by thermally activated diffusion, with higher temperatures improving crystallinity, but under inappropriate conditions they may lead to the formation of secondary phases and chemical inhomogeneity [4,5].

Self-propagating high-temperature synthesis and plasma synthesis proceed under strongly non-equilibrium conditions characterized by short process duration, high temperatures, and rapid cooling, which favors the formation of fine boride phases and limits crystal growth [6,7]. In molecular beam epitaxy, phase formation occurs through controlled atomic growth, allowing the formation of oriented AlB_2 films with a high degree of structural order [8].

Electron-beam processing creates a localized high-temperature cycle followed by rapid crystallization. Although its application to aluminum borides is still limited, the results obtained for other metal–boron systems show significant potential for controlling phase formation through control of the energy density and cooling regime [7–10].

1.2. Influence of the Synthesis Method on the Microstructure

The microstructure of aluminum borides is a determining factor for their mechanical, thermal, and functional properties. The crystal size, distribution of boride phases, porosity, and structural homogeneity depend directly on the synthesis method used and the processing parameters [3–8].

Mechanical alloying accelerates diffusion processes and promotes the formation of finely dispersed boride phases, while conventional high-temperature synthesis provides good crystallinity but often leads to grain growth and lower structural uniformity [3–5]. In contrast, self-propagating high-temperature synthesis, plasma synthesis, and molecular beam epitaxy limit crystal growth and allow the formation of a fine or oriented microstructure with a high degree of crystalline order [6–8].

Electron-beam modification combines localized remelting, rapid crystallization, and processing in vacuum, which creates conditions for obtaining compact surface layers with improved structural homogeneity [7–10]. Data on crystalline AlB_2 thin films show that the microstructure, stoichiometry, and phase composition have a direct influence on the mechanical properties and thermal stability

of the material [11].

1.3. Influence of the Synthesis Method on the Defect Structure and Structural Homogeneity

In addition to the phase composition and microstructure, the synthesis method has a significant influence on the defect structure of aluminum borides. Porosity, residual stresses, microcracks, and other structural imperfections determine to a significant extent the performance characteristics of the material [3–7].

Mechanical alloying leads to the accumulation of crystal defects, which are partially eliminated during subsequent annealing. In contrast, conventional high-temperature synthesis reduces the defect concentration, but under inappropriate conditions it may cause chemical inhomogeneity and the formation of secondary phases [3–5].

Plasma synthesis and electron-beam processing limit the duration of thermal exposure and promote the formation of denser and structurally homogeneous layers. An additional advantage of electron-beam modification is processing in vacuum, which reduces oxidation processes and surface contamination [7–10].

1.4. Comparative Analysis of the Synthesis Methods

The comparative analysis shows that the choice of synthesis method determines the phase composition, microstructure, and properties of aluminum borides. Conventional high-temperature synthesis provides high phase purity and good crystallinity but is associated with higher energy consumption and a risk of grain growth. In contrast, mechanical alloying allows the formation of a finer microstructure but requires subsequent heat treatment [3–5].

Self-propagating high-temperature synthesis, plasma synthesis, and molecular beam epitaxy provide better control over microstructure development and are suitable for obtaining fine powders or oriented thin layers [6–8]. Electron-beam modification complements these technologies through localized energy input and processing in vacuum, demonstrating significant potential for the formation of boride layers with improved properties [7–10].

2. Influence of Synthesis Methods on the Properties of Aluminum Borides

The properties of aluminum borides are directly related to the phase composition, microstructure, and defect state formed during synthesis. Therefore, the production technology determines not only the structure formation processes but also the performance characteristics of the material. Crystal size, structural homogeneity, porosity, and residual stresses have a significant influence on the mechanical, thermal, electrical, and chemical properties of boride materials [1–8].

2.1. Influence of the Synthesis Method on the Mechanical Properties

The mechanical properties of aluminum borides depend primarily on grain size, structural homogeneity, and the distribution of boride phases. A fine-grained microstructure increases hardness and wear resistance, while porosity and secondary phases deteriorate the mechanical resistance [3–7].

High-energy technologies, including mechanical alloying, limit crystal growth and improve the mechanical properties, while prolonged high-temperature heating may reduce the effect of structural strengthening [3–6]. In AlB_2 thin films, the microstructure and stoichiometry have a significant influence on the mechanical properties [11], while electron-beam processing shows potential for increasing the surface hardness and wear resistance of boride systems [7–10].

2.2. Influence of the Synthesis Method on the Thermal Properties

The thermal stability of aluminum borides is determined by the phase composition, crystallinity, and structural homogeneity. A compact microstructure and limited porosity increase the stability at high temperatures [3–7].

High-temperature synthesis provides stable boride phases, while AlB_2 films retain their phase stability up to high temperatures before transforming into AlB_{12} and other borides with high oxidation resistance [11]. In high-energy technologies, thermal stability depends mainly on the processing conditions and microstructure development [7–10].

2.3. Influence of the Synthesis Method on the Electrical Properties

The electrical properties of aluminum borides are determined both by the crystal structure and by structural homogeneity and porosity. Different technologies can result in different electrical conductivity even with the same phase composition [2,4,8].

Molecular beam epitaxy provides high-quality AlB_2 films for the investigation of electronic properties, while electron-beam processing can improve electrical conductivity by reducing porosity and increasing the density of the surface layer [8–10].

2.4. Influence of the Synthesis Method on Chemical Resistance

The chemical resistance of aluminum borides depends on the phase composition, density, and defect state of the material. A more compact and structurally homogeneous microstructure limits the penetration of aggressive media and increases resistance to oxidation and corrosion [2,5].

High-energy technologies, especially electron-beam processing, create dense surface layers during processing in vacuum, which reduces the risk of oxidation and creates conditions for increasing the chemical resistance of boride coatings [7–10].

Figure 1 illustrates the concept "synthesis method → structure → properties," which is the main scientific idea of the present work. Changes in the processing parameters do not directly influence the properties of the material, but act through changes in phase formation, microstructure, and defect state.

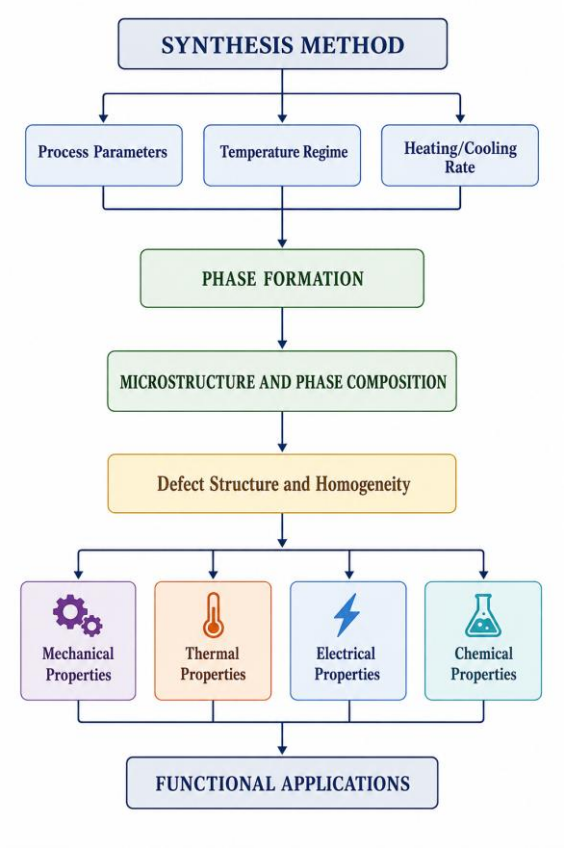


Fig. 1. *Influence of the synthesis method on the structure and properties of aluminum borides*

CONCLUSION

The literature analysis shows that the synthesis technology is a determining factor in the formation of the structure and properties of aluminum borides. The choice of technological approach influences the phase formation, microstructure, structural homogeneity, and defect state of the material, which determine its mechanical, thermal, electrical, and chemical characteristics.

The comparative analysis shows that high-energy technologies create more favorable conditions for the formation of a fine and structurally homogeneous microstructure, while conventional high-temperature synthesis provides high phase purity and good crystalline order. Therefore, the choice of technology should be consistent with the requirements for the structure and functional characteristics of the final material.

The present review confirms that there is a direct relationship between the synthesis technology, the formed structure, and the properties of aluminum borides. Optimization of the processing parameters remains a major direction for the development of materials with controlled structure and improved performance properties.

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