

ABSTRACT

of the PhD dissertation by Alexandr Vladimirovich Revutskiy

Specialty: 8D07202 – Metallurgy

Topic: Research on improving the quality of technical beryllium and enhancement of powder metallurgy processes

Relevance of the Topic. Beryllium is a unique material used in several high-tech sectors of modern industry, ranging from neutron reflectors in nuclear reactors to gyroscopic navigation systems and metal optics. The global beryllium market volume is estimated at 350 metric tons, with a projected growth to 465 metric tons by 2029. According to preliminary data, Kazakhstani beryllium accounts for approximately 25% of global production. However, at present, 99.5% of the Kazakhstani beryllium product range consists of low-value-added products, namely master alloys and semi-finished hot-pressed (HP) billets. A critical strategic vector for Kazakhstan's metallurgical industry is the transition from exporting raw semi-finished products to manufacturing high-tech goods. The existing industrial vacuum hot pressing (VHP) technology provides only a baseline level of structural properties, exhibiting property instability (the non-conformance rate reaches 15–20%) and pronounced anisotropy. Market penetration into the high-technology sector requires beryllium grades with fundamentally superior specialty characteristics, notably high micro-yield strength (precision elastic limit) and consequent dimensional stability. Enhancing the performance characteristics of beryllium is constrained by its inherent brittleness, which stems from its hexagonal close-packed crystal lattice. The traditional strengthening approach via conventional particle refinement has reached its physical limit: further reduction of powder particle size is unfeasible due to high oxidation susceptibility and the inevitable accumulation of impurities. Under these circumstances, alternative methods to enhance beryllium properties must be explored, such as grain boundary engineering. In this framework, beryllium oxide (BeO) acts not as a detrimental impurity, but as a valuable reinforcing constituent capable of substantially increasing product strength and stability. The absence of an established mechanism of reinforcing phase formation and quantitative relationships within the "impurity composition – consolidation parameters – functional properties" system in the scientific literature precludes the development of a stable industrial technology for instrument-grade beryllium. Therefore, investigating the control mechanisms of pressure-assisted hot compaction of beryllium powders to achieve target properties represents an urgent scientific and engineering challenge of substantial importance to both the economic development and scientific potential of the Republic of Kazakhstan.

Aim of the Dissertation. Development of novel scientific principles for quality management of sintered beryllium produced via powder metallurgy routes, and the subsequent advancement of pressure-assisted hot compaction technologies for beryllium powders.

To achieve this aim, the following primary objectives were addressed:

1. Investigation into increasing the mechanical strength properties of industrial hot-pressed beryllium;
2. Clarification of the mechanism through which impurities influence the formation of the reinforcing oxide phase within the microstructure of hot-pressed beryllium;
3. Establishment of quantitative relationships governing the strength properties of beryllium with specific reference to hot isostatic pressing (HIP);
4. Evaluation of the economic efficiency of the developed engineering solutions.

Object of the Study. Industrial technical beryllium powders of various size fractions (from -30 to 180 μm) and consolidated compacts produced via vacuum hot pressing and hot isostatic pressing at the facilities of Ulba Metallurgical Plant JSC (UMZ JSC).

Subject of the Study. Regularities of structural evolution in consolidated beryllium, devitrification mechanisms of grain-boundary oxide phases, and beryllium strengthening processes during thermal consolidation under pressure.

Research Methods. A comprehensive set of modern analytical techniques was employed: inductively coupled plasma mass spectrometry (ICP-MS), gas fusion analysis, photosedimentation analysis, and low-temperature nitrogen adsorption (BET). Microstructural characterization was carried out using scanning electron microscopy with microanalysis (SEM-EDS), transmission electron microscopy (carbon replica technique), and optical metallography. Mechanical testing was performed, and experimental data were statistically evaluated using correlation and regression analyses.

Scientific Novelty of the Work

1. For the first time, based on statistical analysis of industrial beryllium product quality, a mathematical model for controlling the mechanical properties of the resulting material was developed, integrating raw material characteristics and operational process parameters.
2. For the first time, the mechanism of reinforcing phase formation in sintered beryllium was theoretically substantiated and experimentally validated as a controlled devitrification process of the amorphous surface BeO film. The morphology of this phase and its strengthening efficacy were demonstrated to depend on the crystallization regime (homogeneous vs. heterogeneous).
3. For the first time, the decisive role of impurity balance—specifically the Si/Al ratio—in grain boundary formation was experimentally established. It was demonstrated that $\text{Si/Al} < 0.5$ promotes homogeneous crystallization yielding reinforcing discrete particles (120-150nm), whereas $\text{Si/Al} \geq 1.0$ induces a

heterogeneous mechanism leading to oxide coagulation into loose clusters and boundary weakening.

4. For the first time, quantitative relationships linking offset yield strength and micro-yield strength (precision elastic limit) to hot isostatic pressing parameters were established. The resulting analytical expressions represent an extension of the classical Hall–Petch relationship, accounting not only for grain size but also for the dimensions of reinforcing oxide particles.

Practical Significance

1. A flexible technological operating procedure for hot pressing was developed, ensuring quality stabilization of hot-pressed beryllium and reducing production defect rates.

2. Scientific and technological fundamentals were established to expand the manufactured product line by initiating the production of instrument-grade beryllium varieties.

3. The economic efficiency of implementing the study's results was substantiated, demonstrating reduced production costs and establishing a technological foundation for increased profitability through high-value-added manufacturing.

Presentation and Dissemination of Results. The primary findings of the dissertation were presented and discussed at international scientific and practical conferences, including: "Subsoil of Kazakhstan – Foundation of Stability and Prosperity of the Country," dedicated to the 120th anniversary of K. I. Satpayev (Ust-Kamenogorsk, Kazakhstan); VIII International Conference "Deformation and Fracture of Materials and Nanomaterials" (Moscow, Russia); VI International Conference on New Materials and Chemical Industry (Xiamen, China).

Publications. A total of 7 scientific papers were published on the topic of the dissertation, including: 2 articles in peer-reviewed journals indexed in Scopus and Web of Science databases; 5 articles in journals recommended by the Committee for Quality Assurance in Science and Higher Education of the MSHE RK; 1 article in a journal indexed by the Higher Attestation Commission (VAK) of the Ministry of Science and Higher Education of the Russian Federation.

Dissertation Structure and Scope. The dissertation comprises an introduction, six chapters, a conclusion, and a list of references. The manuscript contains 95 pages, 52 figures, and 15 tables. The bibliography includes 87 entries.