ТЕХНИЧЕСКИЕ НАУКИ
И ТЕХНОЛОГИИ

МЕТАЛЛУРГИЯ
МЕТАЛЛУРГИЯ
METALLURGY

DOI 10.51885/1561-4212_2021_4_95
МРНТИ 55.01

B.V. Syrnev[1], N.A. Kulenova[1], A.V. Revutsky1, O.V. Semilutskaya[1], V.Y. Lopatin[2]
[1]D. Serikbayev East Kazakhstan technical university, Ust-Kamenogorsk, Kazakhstan
[2]National University of Science and Technology «Moscow Institute of Steel and Alloys», Moscow, Russia
E-mail: zusan@mail.ru
E-mail: 3007kulenova53@gmail.com
*E-mail: revutskiyav@mail.ru**
E-mail: OSemilutskaya@ektu.kz
E-mail: lopatin63@mail.ru.

SOME PROBLEMS AND PROSPECTS FOR THE DEVELOPMENT OF BERYLLIUM PRODUCTION

БЕРИЛЛИЙ ӨНІМДЕРІ ӨНДІРІСІН ДАМЫТУДЫҢ КЕЙБІР МӘСЕЛЕЛЕРІ МЕН ПЕРСПЕКТИВАЛАРЫ

НЕКОТОРЫЕ ПРОБЛЕМЫ И ПЕРСПЕКТИВЫ РАЗВИТИЯ ПРОИЗВОДСТВА БЕРИЛЛИЕВОЙ ПРОДУКЦИИ

Abstract. *On the world market of beryllium products, there is a steady demand for beryllium metal products for precision instrumentation: gyroscope rotors, metal optics parts, etc. To be used for these purposes, sintered beryllium must meet several requirements, the main of which is to ensure high dimensional stability of finished products. In the conditions of the availability of a production base in the Republic of Kazakhstan for the manufacture of beryllium products, and as a consequence of the potential for expanding the range of beryllium products, an urgent task is to study the material science foundations, production methods, technological techniques with which it is possible to control the special properties of sintered beryllium blanks. The paper presents an overview of the foreign works of the leading research centers on beryllium: USA, Ukraine, Russia. The analysis of studies of the microstructure and nanostructure of grain boundaries, the role of impurities, primarily beryllium oxide, the features of the crystallographic texture that lead to the occurrence of micro stresses, from the standpoint of their influence on the precision properties of beryllium is presented. Based on the critical analysis, the ways of research on the development of scientific foundations for the creation of an instrument grade of beryllium concerning the existing unique equipment of beryllium production in Kazakhstan, which is currently in conservation, are substantiated.*

Keywords: *beryllium, beryllium oxide, precision elastic limit, yield strength, grain size, grain boundary hardening, plastic deformation, hot pressing, fusible impurities.*

Аңдатпа. *Бериллий өнімдерінің әлемдік нарығында дәл Аспап жасау үшін металл бериллийден жасалған бұйымдарға тұрақты сұраныс бар: гироскоптардың роторлары, металл оптика бөлшектері және т.б. осы мақсаттарда пайдалану үшін күйежентектелген бериллий бірқатар талаптарды қанағаттандыруы керек, олардың ең бастысы – дайын өнімнің жоғары өлшемді тұрақтылығын қамтамасыз ету. Қазақстан Республикасында бериллийден бұйымдар жасау үшін өндірістік базаның болуы және соның салдарынан бериллийден өнім номенклатурасын кеңейту үшін әлеуеттің болуы жағдайында материалтану негіздерін, өндіріс әдістерін, технологиялық тәсілдерді зерттеу өзекті міндет болып табылады, олардың көмегімен күйдірілген бериллий* *дайындамаларының арнайы қасиеттерін басқаруға болады. Жұмыста бериллий бойынша жетекші зерттеу орталықтарының шетелдік жұмыстарына шолу берілген: АҚШ, Украина, Ресей. Астық шекараларының микроқұрылымы мен наноқұрылымын, қоспалардың, ең алдымен бериллий оксидінің рөлін, микро кернеулердің пайда болуына әкелетін кристаллографиялық құрылымның ерекшеліктерін олардың бериллийдің дәл қасиеттеріне әсері тұрғысынан зерттеуге талдау жасалды. Сыни талдау негізінде қазіргі уақытта консервациялауда тұрған Қазақстанның бериллий өндірісінің бірегей жабдығына қатысты бериллийдің аспаптық сортын құрудың ғылыми негіздерін әзірлеу бойынша зерттеу жолдары негізделген.*

Түйін сөздер: *бериллий, бериллий оксиді, серпімділіктің дәл шегі, аққыштық шегі, астық мөлшері, астықты шетелге қатайту, пластикалық деформация, ыстық престеу, тез балқитын қоспалар.*

Аннотация. *На мировом рынке бериллиевой продукции наблюдается устойчивый спрос на изделия из металлического бериллия для точного приборостроения: роторы гироскопов, детали металлооптики и др. Для использования в указанных целях спеченный бериллий должен удовлетворять ряду требований, главное из которых – обеспечение высокой размерной стабильности готовых изделий. В условиях наличия производственной базы в республике Казахстан, для изготовления изделий из бериллия, и как следствие потенциала для расширения номенклатуры продукции из бериллия, актуальной задачей является исследование материаловедческих основ, методов производства, технологических приемов, с помощью которых возможно управление специальными свойствами спеченных бериллиевых заготовок. В работе представлен обзор зарубежных работ ведущих центров исследований по бериллию: США, Украины, России. Представлен анализ исследований микроструктуры и наноструктуры границ зерен, роли примесей, в первую очередь оксида бериллия, особенностей кристаллографической текстуры, приводящих к возникновению микронапряжений, с позиций их влияния на прецизионные свойства бериллия. На основании критического анализа обоснованы пути исследований по разработке научных основ создания приборного сорта бериллия применительно к имеющемуся уникальному оборудованию бериллиевого производства Казахстана, находящемуся в настоящее время на консервации.*

Ключевые слова: бериллий, оксид бериллия, прецизионный предел упругости, предел текучести, размер зерна, зернограничное упрочнение, пластическая деформация, горячее прессование, легкоплавкие примеси.

Introduction. Beryllium is a metal having a unique complex of physico-mechanical and nuclear-physical properties, which determines its use in some important high-tech branches of technology. From the point of view of the structure of the crystal lattice and the uniqueness of the physico-mechanical properties, beryllium without exaggeration can be attributed to the category of paradoxical metals. It has high electrical and thermal conductivity, heat resistance, melting and boiling points, corrosion resistance, dimensional and configuration stability. In terms of specific characteristics of rigidity, strength and heat capacity, it surpasses all other materials, and is comparable in density to the lightest magnesium alloys.

The use of beryllium in technology is continuously expanding, despite many disadvantages – cold breaking, toxicity and high cost. This is due to the great technical advantages, and in some cases, the economic benefits of replacing beryllium with traditional materials. Beryllium is indispensable in nuclear engineering products and aerospace structures (Figures 1...3) [1]:

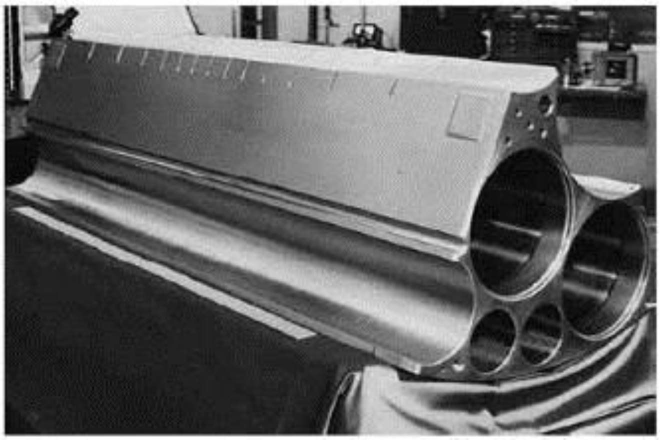


Figure 1. Beryllium neutron reflector section

Figure 2. Beryllium brake discs

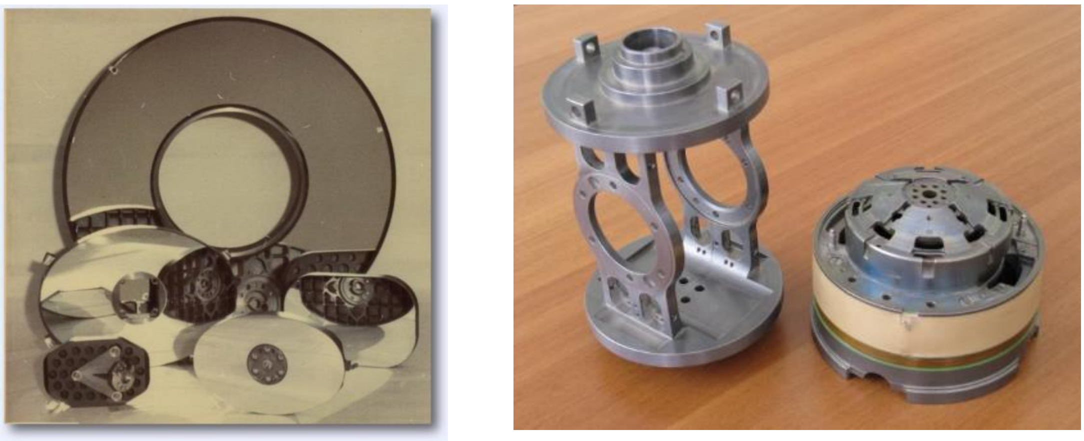
Currently, the basis of the nomenclature of beryllium production in Kazakhstan consists of various types of beryllium ligatures, which consumer enterprises use to produce copper-beryllium bronzes of the BrB type, high-modulus aluminum alloys of the ABM type, etc. Ligatures are produced by methods of classical metallurgy: carbothermic method and direct fusion of components.

At the same time, beryllium production has a significant potential for expanding the range of products due to the development and production of products for special instrumentation. It has a separate 602P building, in which, to date, unique equipment has been preserved:

– automatic line of the company "Leibold-Hereus" for the production of spherical beryllium powders by electron beam sputtering and subsequent encapsulation before pressing;

– gasostat of VNIIMETMASH design with a working diameter of 1600 mm for cold isostatic pressing of powders under pressure up to 4000 bar;

– VNIIMETMASH gasostat with a working diameter of 1100 mm for hot isostatic pressing under pressure of 1000 bar;



а *б*

Figure 3. Details of special beryllium instrumentation: a – space mirror; b – gyro parts;

The existing technical base can be considered as a basis for further development of beryllium production and improvement of its economy through the development and production of special instrumentation products. However, in addition to the technical base, which can ensure the production of large-sized products with isotropic properties, it is necessary to meet the requirements for special properties that ensure dimensional stability of parts during exploitation [2, 3]. The use of beryllium in gyro-instrumentation and metal optics, due to the high specific stiffness characteristics inherent in it by nature (Table 1), places high demands on the dimensional stability of products, ensuring which is already the task of beryllium manufacturing technologists.

Table 1. Comparative values of some physical properties of beryllium and other metals

Metal	Melting point C	Density, g/cm^3	Modulus of elasticity, GPa	Specific modulus of elasticity $(E/\gamma)10^{-7}$, м
Os	2700	22,5	5700	2,53
Ir	2454	22,4	525	2,34
Re	3340	21,0	470	2,25
W	3377	19,1	360	1,88
B	1700	3,3	400	12,16
Be	**1284**	**1,85**	**300**	**16,60**
Al	657	2,7	71	2,63
Mg	651	1,76	44	2,5
Ti	1750	4,5	105	2,44
Fe	1535	7,8	210	2,65
Cu	1083	8,9	125	1,4
Zn	420	7,1	100	1,55

Dimensional stability is indirectly characterized by a precision elastic limit (PPU), which is equal to the mechanical stress on the sample $\sigma 0.005$, causing a residual deformation of 0.005 %. Currently, this characteristic of beryllium products is not determined at the plant, and, most importantly, there is no knowledge, experience, statistics on how to manage this quality indicator. Regular hot-pressed billets from technical beryllium TGP-56 have $\sigma 0.005$ from 10 to 50 MPa, which is not enough for «instrument makers».

In this regard, the work on the study of materials science mechanisms, techniques, technological regulations governing the strength properties of sintered beryllium blanks is relevant..

Literary review. The history of the production of beryllium products, since the first attempts at its structural application in the 50s, largely boils down to the fight against its low plasticity. A generalized analysis of the history of domestic and foreign research in the field of materials science and beryllium technology allows us to identify two fundamental approaches to solving the problem of creating a structural material from a brittle metal. Each of these approaches is aimed at creating an optimal structure, from the point of view of researchers, and the difference lies in the placement of accents in the chain composition→structure→property.

The first approach, actively developed by the Kharkiv school of Metallophysicists, proceeds from the premise of the prevailing value of the composition and is therefore focused on obtaining the purest metal possible [4]. This approach is based on the results of studying the fundamental properties of the beryllium crystal lattice, sliding systems, and destruction of high-purity beryllium mono- and polycrystals. It was thanks to the study of ultrapure metal that the fundamental laws of plastic deformation and destruction were established, the phenomenon of beryllium superplasticity was discovered and investigated, technological processes for producing thin vacuum-dense foils were developed. In the course of comprehensive studies, it turned out that the fragility of beryllium is determined by the peculiarities of its electronic structure (the presence of a covalent component) and therefore cannot be eliminated in principle. At the same time, these results of scientific research within the framework of this approach formed the basis of fundamental ideas about the nature of the fragility of beryllium. One of the directions implemented in the industry of this scientific school was the development and introduction into production of beryllium distillation technology and the production of high-purity beryllium in metallic impurities that meets the requirements of nuclear reactor engineering. However, the reduction of hardening impurities (the content of metal impurities was in the range from 10-3 to 10-5 %) reduced the yield strength by 25...30 %. This fact indicates that high-purity beryllium is not effective for «instrument» use.

Subsequently, during the formation of the beryllium industry in Kazakhstan, it became obvious that the use of foundry technology for the production of beryllium products is extremely limited. All the progress in improving the mechanical properties of structural beryllium produced by the industry of Kazakhstan is due to the development of powder technology, developed largely by the efforts of VNIINM after academician A. Bochvar [1, 5].

Materials and methods of research. The effect of microstructure on the mechanical properties of beryllium. To harden metals, in general, various methods are used: solid-solution, grain-boundary, dislocation, dispersion hardening.

As experimental studies have shown, alloying and obtaining solid solutions based on beryllium has few prospects, firstly, due to the low solubility of the elements in it, and secondly, a sharp drop in plasticity, which made the alloy non-technological [6].

The most promising direction of increasing the strength properties of beryllium and simultaneously increasing the technological plasticity was the method of grain boundary hardening. The influence of grain sizes on the mechanical properties of beryllium was studied in the middle of the last century. It was found that the reduction of grain sizes in cermet beryllium from 61 to 17 microns led to an increase in the tensile strength from 206 to 343 MPa [7]. The mechanical properties of beryllium obtained by powder metallurgy methods, other things being equal, are determined by the size of the initial powder. A finer powder contributes to the formation of a finer-grained structure in semi-finished products, which causes increased strength and plastic properties. With a decrease in grain size, the yield strength and temporary resistance to rupture of beryllium increases [5]. As for other metals, the relationship of the yield strength of beryllium with the grain size can be described by the Hall-Petch equation (Figure 4):

$$\sigma_T = \sigma_0 + K_{\text{т}} d^{-1/2},$$

where σ_T – yield strength; σ_0 – is the yield stress at $d^{-1/2} = 0$, depending on the purity of the metal 40-140 MPa; K_T – is a constant associated with the stress required to transfer sliding from one grain to another, K_T = 14,5-29,0 МПа×мм$^{1/2}$; The constant $K_{\text{т}}$ characterizes the strength of blocking dislocations during the transfer of deformation from grain to grain and is determined by the ratio:

$$K_{\text{т}} = \sigma_d (2L)^{1/2}$$

where σ_d – is the dislocation separation stress from the anchorages; L is the distance between the dislocation source and the grain boundary.

The dependence of the Hall-Petch equation for hot-pressed beryllium of industrial purity containing 3,3-5,3 % BeO, determining the yield strength, is shown in Figure 1.4, with values σ_0≈73,5 MPa, $K_{\text{т}}$≈27,5 MPa [6],

The dependence of the destructive stresses σ_P on the grain size is determined by the Petch-Stroh ratio:

$$\sigma_P = \sigma_0 + K_P d^{-1/2}$$

Like the ratio for σ_T this ratio is derived empirically by processing experimental results, but it can also be interpreted based on dislocation representations of destruction.

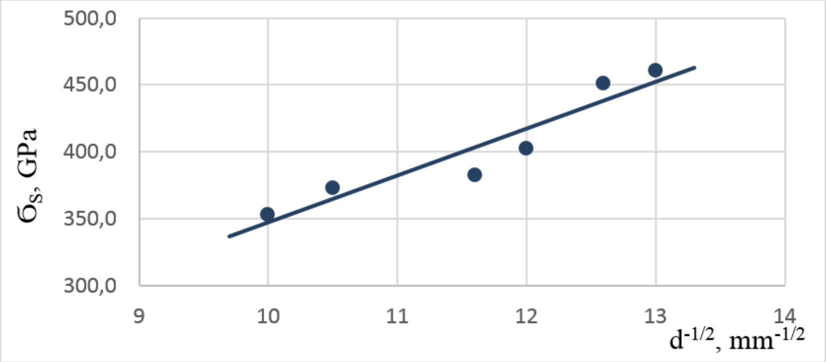


Figure 4. Dependence of yield strength on grain size for hot-pressed beryllium

The dependence of breaking stresses and tensile strength on dimensions for hot-pressed beryllium has already been investigated and shown in Figure 5, with tabular values σ_0≈ 98,1 MPa, K_P≈ 29,2 MPa [8]. These studies also showed that the value σ_0 does not depend on the texture of the metal and has a weakly pronounced dependence on the content of impurities, and all values of the constant σ_0 for beryllium, regardless of the method of production, are in the range 98÷147 MPa.

The constant K_P depends on the texture of beryllium: the minimum values of 19,6÷29,4 MPa correspond to a metal with an isotropic structure obtained by hot pressing powders, and the maximum values - up to 98 МПа – to a highly textured metal. An increase in deformation leads to an increase in K_P.

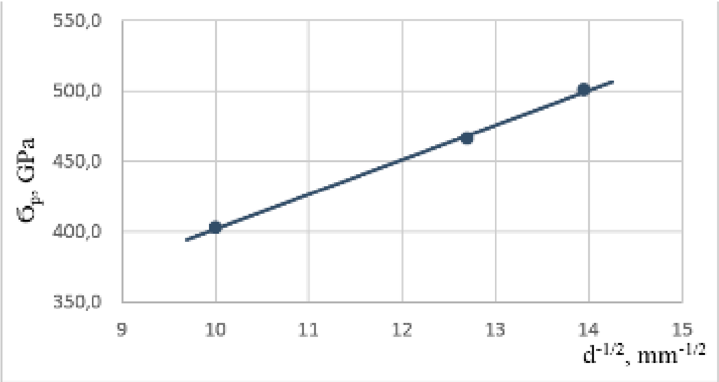


Figure 5. Dependence of the tensile strength on the grain size for hot-pressed beryllium

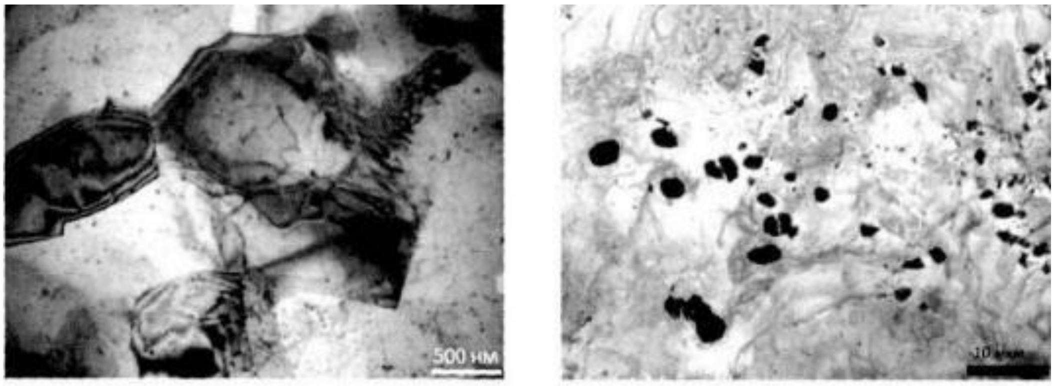
Based on these scientific developments, beryllium production in Kazakhstan developed in the period from the 60s to the 80s of the last century. The dispersion of the initial powders gradually decreased as specialized equipment was developed. Initially, the grade PTB-600 (powder of technical beryllium with a size of 600 microns) was mastered, then PTB-200, PTB-56. The desire to obtain a grade of beryllium with a high PUF caused the work to further reduce the dispersion to – 30 microns, -20 microns. However, these works were not crowned with success, because the resulting powders were rapidly oxidized (burned), were non-technological (there was no fluidity of powders), existing compaction technologies did not give stable results in terms of material quality. Observed at the same time: an increase in cost, pyrophoric powders, dustiness of production facilities, an increase in the content of impurities, worsened environmental and economic indicators of production.

For many years, work has been underway to investigate the possibility of obtaining nanopowders and nanocrystalline beryllium (Table 2) using the hydride method [9].

Table 2. Chemical composition of nanocrystalline beryllium obtained by VNIINM hydride technology and high-purity beryllium IF-1 by Brush Wellman

Nanocrystalline beryllium obtained by hydride technology												
Elements	Li	Mg	Al	Ca	V	Cr	Mn	Fe	Co	Ti	Ba	Cu	Ni
Content, ppm (w)	0,03	2	4	40	2	2	2,5	45	0,1	0,1	0,4	1,5	1,7
High-purity beryllium IF-1 from Busch Wellman													
Elements	Zn	Mg	Al	Ca	Mo	Cr	Mn	Fe	Ti	Si	C	Cu	Ni
Content, ppm (w)	100	60	100	200	10	35	30	300	10	100	300	50	200

Compact beryllium with a grain size of 20...30 nm is obtained from this material by hot pressing. The author notes that «the size of oxide inclusions is an order of magnitude smaller than in the standard technical beryllium» (Figure 6).



a *b*

Figure 6. Morphology of BeO particles in beryllium:
a – beryllium obtained by hydride technology; b – technical hot-pressed beryllium

This is, without a doubt, a promising direction, which has not yet been brought to industrial implementation.

The influence of the features of the crystallographic structure on the mechanical properties of beryllium. VNIINM has developed a concept on the determining effect of residual thermal micro stresses of RTM on the mechanical properties of beryllium [10]. Beryllium has limited plasticity at room temperature, although it does not meet the Mises-Taylor criterion, which requires five independent sliding systems to maintain continuity during plastic deformation of a polycrystalline material. Beryllium has only four independent sliding systems (in the planes of the basis and prism), i.e. the totality of the mechanisms of plastic deformation known for beryllium does not allow us to count on achieving any plasticity at all. The authors explain this paradox by the presence in beryllium of effects associated with the uniqueness of the thermophysical and physicomechanical properties of its crystallites. In particular, the anisotropy of the thermal coefficient of linear expansion of a beryllium single crystal along (a||) and across (a^) the hexagonal axis, which in combination with high elastic modules causes large residual thermal micro stresses (RTM) in a polycrystalline metal It is known that at 20 ºC the value a|| = 8,7·10–6 K–1,a^ = –10,2·10–6 K–1, i.e. the anisotropy is ~20 %. As a result, after cooling in polycrystalline beryllium, RTMS will inevitably arise, the value of which will be determined by the ability to relax stresses during cooling. It is important that in polycrystalline beryllium at room temperature, each grain is compressed along the hexagonal axis and stretched in transverse directions, thereby complicating the destruction along the planes of the basis. Since the destruction along the planes of the basis is the main type of destruction of beryllium, the strength should increase with the growth of RTM. Figure 7 shows the results of measurements of tensile strength and elongation.

The analysis of the dependencies shows that the tensile strength increases linearly with the growth of RTM, the elongation has a maximum at a certain value of RTM.

Assuming that the tensile strength and elongation are functions (RTM), a relationship is also established between them (Figure 8).

For statistical processing and construction of this dependence, a large array of test results of industrial blanks was used. The constructed dependence is a phenomenological model.

In Figure 8, three zones (1-3) can be distinguished. In zone 1, a metal with low strength has a good ability to relax RTM and therefore may be preferable for large-sized products or heat-resistant structures operating under conditions of sudden temperature changes.

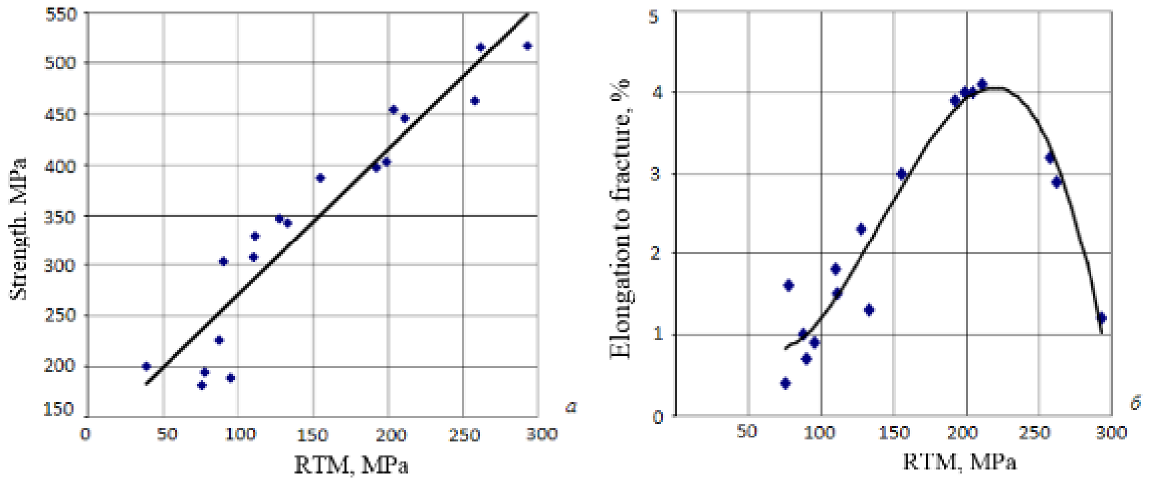


Figure 7. Dependence of tensile strength (a) and elongation to fracture (b) on the magnitude of residual thermal micro stresses in hot-pressed beryllium at room temperature

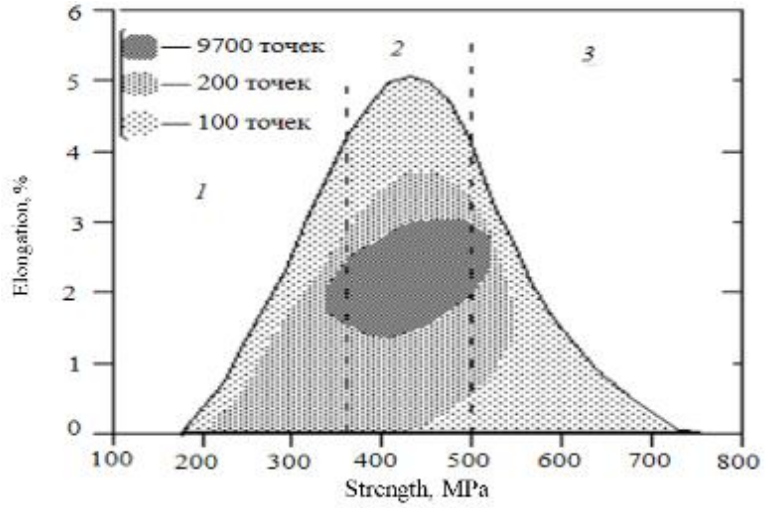


Figure 8. Correlation between elongation and strength for hot-pressed beryllium

In zone 3 with high strength, the material belongs to the category of poorly relaxing and can be used for the manufacture of small products that require high dimensional stability. Zone 2 corresponds to the properties of beryllium, which has the maximum work of destruction, i.e. for general structural applications.

It is obvious that grain-boundary oxide inclusions, which are always present in the structure of powdered beryllium, prevent the implementation of intergranular slippage, thereby maintaining a higher level of residual micro stresses in the powdered metal compared to beryllium of foundry origin. It is also obvious that the amount and degree of dispersion of grain-boundary oxide inclusions should have a significant effect on the magnitude of micro stresses fixed at room temperature and, accordingly, the tensile strength. It is the discretionary modes of deformation that to some extent compensate for the deficiency of sliding systems in beryllium and ensure the existence of noticeable plasticity in polycrystalline metal.

The influence of impurities on the mechanical properties of beryllium. The beryllium industry of Kazakhstan produces beryllium products mainly using powder metallurgy methods – by obtaining powders and their further consolidation into a compact sintered material, mainly by hot vacuum and isostatic pressing methods.

One of the most important factors distinguishing the structure of sintered beryllium from the structure of cast beryllium is the presence of inclusions of beryllium oxide at the grain boundaries in an amount of up to several percent, which largely determined both the possibility of long-term high-temperature processing without catastrophic grain growth and the control of the physicomechanical properties of compact material.

When using classical grinding methods (shavings, abrasion, and grinding in an air atmosphere), the content of beryllium oxide on the surface of the particles increases rapidly with a decrease in particle size in proportion to the total surface of the crushed particles.

The first study of the structure of the oxide film on the surface of beryllium was carried out more than 80 years ago, as a result of which, it was found that at room temperature, a uniform thickness, dense, and very thin BeO film is formed on the metal. Its thickness is approximately 0.01...0.02 microns [11]. The role of beryllium oxide located at the grain boundaries of compact beryllium, according to various authors, is contradictory. Some researchers believe that beryllium oxide particles are stress concentrators that beryllium embrittles due to premature destruction of the material [12]. Others consider beryllium oxide not only a hardener but in certain quantities – increasing plasticity [11].

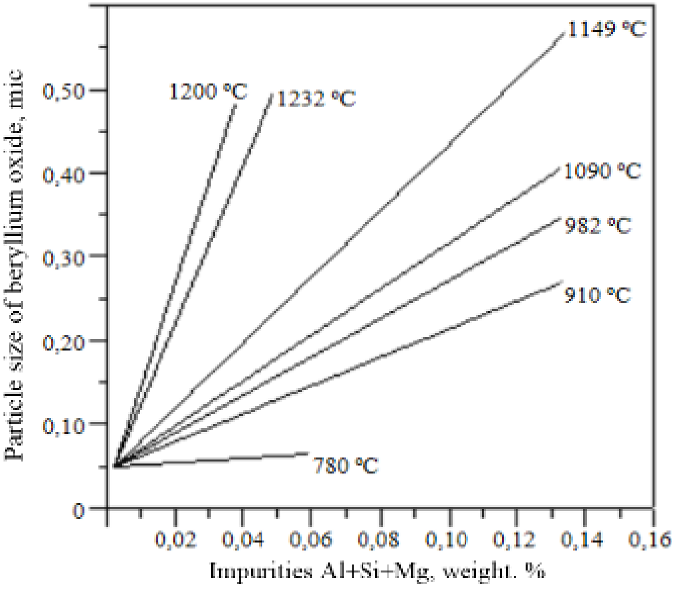


Figure 9. Effect of fusible impurities on the particle size of beryllium oxide at the grain boundaries of hot-pressed beryllium

When studying the morphology of oxide particles and their changes in the presence of impurities using transmission electron microscopy, it was shown that a high-purity material (impurity content: BeO – 0,9 %; Fe – 0,075 %; Al – 0,06 %; Si – 0,06 %, Mg – 0,08 %), compacted by hot isostatic pressing at a relatively low temperature (903OC), contains beryllium oxide in the form of dispersed particles up to 0.04 microns in size at grain boundaries (Figure 9) [13]. The material of the dirtiest grades (Impurity content: BeO – 2 %; Fe – 0,18 %; Al – 0,16 %; Si – 0,08 %, Mg – 0,08 %), obtained by hot pressing at temperatures of 1075-1160 ºC, contained BeO particles with a size of 0,15-0,4 microns in the form of clusters.

Dispersed inclusions and accumulations of beryllium oxide at the boundaries of beryllium grains are formed as a result of destruction and coagulation during compaction of the initial beryllium powders [14, 15]. Figure 9 shows the dependences of the average size of grain-boundary oxide inclusions on the content of fusible impurities for different hot pressing temperatures.

The general pattern is that with an increase in temperature and the content of the sum of fusible impurities (aluminum, silicon, magnesium form fusible eutectic with beryllium), the average size of inclusions increases. The abundance and complexity of the processes involved in the formation of the oxide structure lead to the fact that in beryllium, the formation of the oxide structure effectively occurs mainly on the free surfaces of beryllium particles and slows down quickly after compaction of the powder body and «closing» of the powder surfaces.

At temperatures above 760 °C, the creep resistance directly depends on the presence of aluminum, silicon, and magnesium in the form of a liquid phase at the grain boundary [11]. Catastrophic destruction did not occur at the same time because the volume of the liquid phase, usually present in beryllium, is insufficient for the formation of a continuous film at the boundary.

In recent years, a significant number of studies have been published on the role of impurities in sintered beryllium, carried out by employees of the Kharkiv Institute of Physics and Technology (Ukraine) and the Federal Scientific Center «VNIINM» named after Academician A. Bochvar, the Russian Scientific Center «Kurchatov Institute» (Russia) [16].

The behavior of the oxide film on the surface of beryllium was studied by reactor specialists about the use of beryllium as a material in contact with the core of a thermonuclear reactor, in particular ITER. Davydov D. A. and the staff of the RSC "Kurchatov Institute" investigated the behavior of beryllium oxide film in various media (air, oxygen, carbon dioxide, moisture). These gases are the ingredients of the gas medium that occurs in the pores when beryllium powders are heated [17]. Following the Pilling—Bedworth rule, if the volume of metal oxide formed during the reaction of metal and oxygen is less than the volume of the reacted metal ($\beta < 1$), the metal oxide film may have a discontinuous cellular structure and cannot reliably protect the metal from further high-temperature oxidation. If the volume of the metal oxide exceeds the volume of the reacted metal ($\beta > 1$), the oxide film covers the metal with a continuous layer and grows freely from the outside. For beryllium, the ratio of the volume of oxide (BEO) to the volume of the reacted metal at 300 K $\beta = 1.6$. In addition, the protective characteristics of the oxide film are affected by the strength and plasticity of the oxide, its adhesion to the metal, the ability of the oxide to peel off, and the solubility of the oxide in the metal.

The authors [16, 17] claim that a large difference between the thermal expansion coefficients and the density of beryllium and VeO causes compressive stress in the beryllium oxide film and its cracking. This voltage increases over time as the temperature increases. The lower the temperature, the longer it takes to break the film. At temperatures below 1000 K in air or oxygen, cracks can «heal», while at temperatures above 1200 K cracking becomes dominant (Figure 10).

In [16], the mechanisms of formation of discrete oxide particles at grain boundaries were confirmed as a result of the processes of destruction and coagulation of the oxide film at powder boundaries during compaction, and important features of the coagulation process of BeO inclusions and their effect on the mechanical properties of hot-pressed beryllium were noted (Table 3). The table shows that when the pressing temperature decreases from 1200 до 1080

^{0}C the size of BeO particles decreases 210 до 110 nanometers, the strength increases from 368 до 517 MPa.

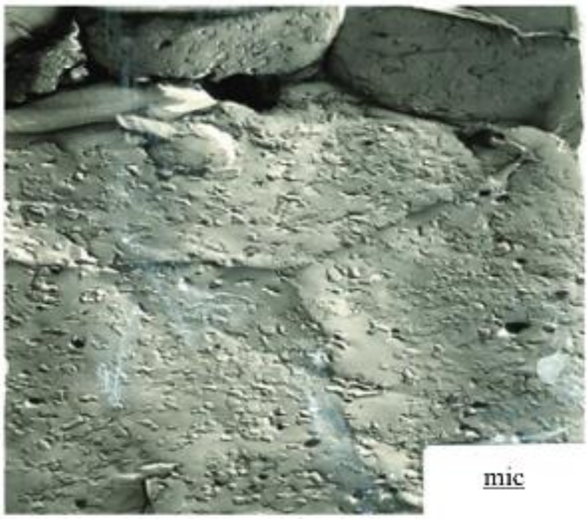


Figure 10. Fractogram of a fracture of a sample of hot-pressed beryllium PTB-56 with inclusions of beryllium oxide

Table 3. Dependence of the mechanical properties of hot-pressed beryllium PTB-56 on the parameters of hot pressing

Initial powder (Type)	Content BeO, weight. %	Hot pressing mode			D, mic	σ_B, MPa	$\sigma_{0,2}$, MPa	δ,%	RTM, MPa	dBeO, (est.) mic
		T, °C	P, MPa	V, mm/min						
PTB-56	1,4	1080	500	1,15	17	517	418	4	280	0,11
		1140	650		19	417	298	2	200	0,17
		1200	650		21	368	290	1	160	0,21

Note: D – is the average grain size of beryllium, d- is the average particle size of beryllium oxide, RTM is the residual thermal micro stresses.

The effect of increasing the mechanical properties of hot-pressed beryllium with a decrease in the particle size of beryllium oxide is considered by the authors within the framework of the theory of the occurrence of residual thermal micro stresses caused by the anisotropy of the compressibility of beryllium along various crystallographic axes. Within the framework of this paradigm, with a decrease in the size of the "wedging" particles, their softening effect decreases..

Results and their discussions. Several studies, in particular [18], were devoted to the study of the effect of oxide inclusions on the microplastic deformation of beryllium, which characterizes such a property of beryllium as the precision elastic limit, i.e. an indicator important for the use of beryllium in special devices. To study the precision characteristics by the method of mechanical hysteresis under static tension, the authors used a machine of the design of the NSC HFTI. The speed of movement of the capture was 5,4·10–6 c^{-1}. A cylindrical elastic element with a strain gauge load measuring system was used as a force meter. To measure the deformation of the samples, resistance sensors with a base of 20 mm equal to the length of the working part of the samples were used. The error in determining the load did not exceed ± 1%, deformations $\varepsilon = \pm 2\cdot10^{-7}$. The dimensions of the images: the length of the working part is 20 mm, the crosssection is 3–3,5 мм^2. In experiments, the following values were determined in the field of micro deformations (10^{-7}–10^{-3} units of relative deformation – u.r.d.).

− microscopic elastic limit σ_E – is the stress at which a deviation from the linear elastic behavior of the material is detected during loading;

− microscopic yield strength σ_A – the stress at which the first residual deformation is observed $\varepsilon = 2 \cdot 10^{-7}$;

− residual deformation ε after each load cycle of the sample;

− young's module E in the field of microplasticity.

The main attention in the work was paid to powder beryllium compacted by cold and hot isostatic pressing (CIP-HIP). Its microplasticity characteristics in the initial state and after prolonged exposure are given in Table 4, the characteristics of some other beryllium varieties considered are also presented there.

The analysis of the table shows that the main factors influencing the values of σ_E, σ_A and the microflow voltage σ, are the particle size and chemical composition of the powder, as well as the technological modes of metal production.

Table 4. Microplasticity characteristics of various beryllium varieties in the initial state and after long-term storage

Material	Method of obtaining	Storage duration, th. h.	E, GPa	σ_E, MPa	σ_A, MPa	σ_A, MPa with ε		
						$1 \cdot 10^{-6}$	$2 \cdot 10^{-6}$	$5 \cdot 10^{-6}$
CIP-HIP	CIP-HIP powder of technical purity	Исходное состояние	359	11,6	35,3	73	117	258
		14,8	-	11,9	29,9	-	53	150
CIP-HIP$_{Sph}$	CIP-HIP grinding spherical powder	Исходное состояние	348	11,4	34,0	68	158	229
		15,5	-	8,1	12,1	-	27	120
HIP$_{Sph}$	HIP of spherical powder of technical purity	Исходное состояние	340	17,2	41,0	49	56	80
		11,8	-	16,4	44,6	-	79	112
HIP$_{Sph\,D}$	HIP of distilled metal spherical powder	Исходное состояние	335	-	8,4	6,3	8,8	13
		11,8	-	-	9,1	-	18	23

Conclusion. 1) The work of many foreign researchers and the production practice of beryllium production have shown that beryllium oxide at the grain boundaries of sintered beryllium can be either in the form of individual monoparticles or clusters. Inclusions of oxide particles are a modifying ingredient of the nanostructure of the boundaries of metallic beryllium grains, as they increase mechanical properties: strength, plasticity, and micro-fluidity indicators (with the contents of the BeO within the current production specifications). In this regard, powdered beryllium can be considered as a dispersed-hardened composite material in which the oxide is a reinforcing strengthening phase.

2) The data available in the literature describe the mechanism of formation of inclusions of the oxide phase at the boundaries of beryllium grains, as a result of cracking of a solid oxide film under the action of stresses arising during heating due to differences in the coefficients of thermal expansion of beryllium and its oxide, followed by coagulation into particles and conglomerates. This conclusion seems to be debatable, requiring clarification, since knowledge of the mechanism of degradation of the beryllium oxide film will allow us to develop ways to control the properties of sintered beryllium.

3) The dispersion of the oxide reinforcing phase, on which the modifying effect depends, is affected by the presence of low-melting impurities Al, Si, Mg. There are separate data on the ef-

fect of the total value of these impurities on the size of oxide particles and the mechanical properties of sintered beryllium. However, there is no data on the role of the ratio of these impurities, which can also affect the process of oxide coagulation due to changes in the properties of eutectic (wettability of oxide, surface tension, etc.). In addition, quantitative patterns about the complex effect of the size of the initial particles, the grain size of compact beryllium, the size of reinforcing particles, technological modes on the quality of sintered beryllium are of interest.

4) Thus, to create scientific foundations for the management of precision mechanical properties of "Kazakh" beryllium, the development of new varieties of products, and the expansion of the nomenclature of beryllium production, it seems appropriate to direct the research carried out within the framework of doctoral dissertations to:

- investigation of the mechanism of degradation of the beryllium oxide film, morphological and structural features of the formation of the reinforcing phase in sintered beryllium.
- development of quantitative dependences of the precision elastic limit of sintered beryllium on the complex effect of grain size, dispersion of reinforcing particles, and temperature conditions of hot isostatic pressing.

References

1. Tuzov Yu.V. Berillij – material yadernoj i termoyadernoj tekhniki/ Yu.V. Tuzov, V.A. Gorokhov, Ya.D. Pakhomov, V.N. Pronin. Voprosy` atomnoj nauki i tekhniki. 2009. vy`p. 2. S. 124-127.
2. Everitt C.W.F. et all. Gravity Probe B: Final results of a space experiment to test general relativity// Physical Review Letters. 2011. 10. P. 2216.
3. Yul`metova O.S., Shherbak A.G., Chelpanov I.B. Pod red. Valetova V.A. Speczial`ny`e tekhnologii izgotovleniya preczizionny`kh uzlov i e`lementov giroskopicheskikh priborov. Uchebnoe posobie. - SPb.: Universitet ITMO, 2017. - 131 s;
4. Papirov I.I., Tikhinskij G.F. Fizicheskoe metallovedenie berilliya. - M. : Atomizdat, 1973. - 284 s.
5. D.Webster and D.D. Crooks, Creep mechanisms in beryllium, Met. Trans. 7A. 1976. P. 1307-1315.
6. Logerot G.M. Conference Internationale sur la Metallurgie du Beryllium. Grenoble. 1965, p.471.
7. Papirov I.I., Tikhinskij G.F. Plasticheskaya deformacziya berilliya.- M.: Atomizdat, 1973. – 304s.
8. Cooke P.W. e. a. Metallurgical Trans., 1971, 2, p. 1297;
9. Yu.E. Markushkin. Berillij dlya rentgenovskoj tekhniki - novy`e vozmozhnosti nanokristallicheskogo materiala/ Markushkin Yu.E., Gorlevskij V.V., Zabrodin A.V., Tuzov Yu.V. Voprosy` atomnoj nauki i tekhniki. Seriya: Materialovedenie i novy`e materialy`. 2012. vy`p. 1. – S. 130-136.
10. Yu.V. Tuzov. Mekhanizmy` relaksaczii ostatochny`kh termicheskikh mikronapryazhenij v berillii/ Tuzov Yu.V., Khomutov A.M. Czvetny`e metally`. 2009. vy`p. 12. S.79-82.
11. D.Webster and D.D. Crooks, Creep mechanisms in beryllium, Met. Trans. 7A. 1976. P. 1307-1315.
12. Papirov I.I. Okislenie i zashhita berilliya. – M.: Metallurgiya, 1968. – 121 s.
13. Webster D., Crooks D.D., Vidoz A.E. The effect of oxide dispersion on the recrystallization of beryllium, Met. Trans. 1974. Vol. 4. No 12. P. 2841-2847.
14. D.Webster, Effect of low melting phases on the elevated temperature microstructural stability of hot pressed beryllium, Met. Trans. 6A. 1975. P. 803-808.
15. Turner G.I., Lane R.A. The effect of powder particle size on the mechanical properties of hot pressed P1 beryllium. — In: Proc. Beryllium 1977 Conf. London, Oct., 1977, p. 1/15.
16. Yu.V. Tuzov. Berillij - sostoyanie, problemy`, vozmozhnosti i perspektivy`/ Tuzov Yu.V., Krasnoshhekov E.S., Markushkin Yu.E. VANT. Ser. Termoyaderny`j sintez. 2011. vy`p. 2, S. 21-27.
17. Davy`dov D.A. Obrazovanie i degradacziya oksidny`kh plyonok na berillii/ D.A. Davy`dov, O.V. Kholopova, B.N. Kolbasov. 2010, vy`p. 2. S. 39-48.
18. Ivanczov V.I. Izuchenie mikroplastichnosti i razmernoj stabil`nosti razlichny`kh sortov berilliya/ Ivanczov, A.A. Nikolaenko, I.I. Papirov, A.I. Pikalov, V.S. Shokurov V.I. Vestnik TGU. 2010. t.18. vy`p. 4. S. 1556-1558.