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B.K. Rakhadilov[1], A.B. Kengesbekov[2,3]✉, N.M. Magazov[2],
A.A. Kusainov[2], L.S. Kairbaeva[2,3], Y.S. Molbosynov[2]

[1] *“PlasmaScience” LLP, Ust-Kamenogorsk, Kazakhstan;*
[2] *D. Serikbayev East Kazakhstan Technical University, Kazakhstan, Ust-Kamenogorsk;*
[3] *Institute of Composite Materials/LLP, Ust-Kamenogorsk, Kazakhstan*

Study of the Effect of Thermomechanical Treatments on the Property of Beryllium Bronze in Order to Expand Its Application

The article is devoted to the study of the influence of thermomechanical treatments on mechanical and physicochemical properties of beryllium bronze in order to expand its application in modern technologies. This paper studies the influence of different modes of thermomechanical processing on the structure and properties of beryllium bronze. The mechanism of influence of these methods on modification of alloy microstructure, which directly affects its performance characteristics, is described. The obtained results allow expanding the areas of application of beryllium bronze in industry, aircraft construction and other sectors. And also the main conclusions are that the introduction of advanced methods of thermomechanical processing helps not only to improve the physical characteristics of bronze, but also makes it possible to use this material in new areas, such as aerospace and automotive industries. The article is of importance for specialists in the field of materials science and engineering, as it provides new data and recommendations that can improve the processes of production and operation of beryllium bronze products.

Keywords: beryllium bronze, heat treatment, mechanical treatment, thermomechanical treatment, aging, hardening, material microstructure, equal-channel angular pressing (ECAP)

✉*Corresponding author*: Kengesbekov Aidar, aidar.94.01@mail.ru

Introduction

Beryllium bronze is a unique copper alloy containing 0.5 % to 3 % beryllium and, in some cases, other alloying elements such as cobalt or nickel [1]. This material combines high strength, non-magnetization, wear resistance and corrosion resistance, which makes it in demand in various industries. Due to its heat treatability, beryllium bronze exhibits exceptional mechanical properties, including strengths up to 1400 MPa, which is far superior to other copper alloys [2]. Its thermal conductivity of 107 W/m·K is also 3–5 times higher than that of tool steel, which opens up additional opportunities for its application.

Due to its unique characteristics, beryllium bronze is used in a wide range of applications, from the production of tools for hazardous environments to high-tech components in the aerospace industry [3]. Its non-magnetic nature and its ability to prevent sparks make the material indispensable for the manufacture of tools used in hazardous environments such as coal mines, drilling rigs and grain elevators. In addition, beryllium bronze is used in electronics, production of musical instruments and devices for precise measurements, as well as in the production of springs, contacts and bearings [4]. The main producers of beryllium are the USA, China and Kazakhstan. In total, about 300 tons of beryllium are produced in the world per year.

BrB2 is a tin-free, pressure-treated beryllium bronze. The chemical composition of BrB2 alloy is described in GOST 18175-78 and includes the following components: copper 96.9–98.0 %, beryllium 1.8–2.1 %, nickel 0.2–0.5 % and up to 0.5 % of impurities.

Thermomechanical treatment is an important tool to improve the properties of beryllime bronze [5]. It is an effective tool for optimizing the properties of beryllium bronze. The development of new TMT modes will allow to significantly expand the application area of this unique material, providing an increase in its performance characteristics and durability. The processes of hardening, aging and plastic deformation at high temperatures lead to changes in its microstructure, which in turn affects its mechanical and physical properties [6]. For example, the use of aging allows the formation of ordered phases in the alloy structure, which increases its hardness and tensile strength. This makes beryllium bronze even more adaptable to different operating conditions. Aging is a key stage of heat treatment that contributes to the hardening of beryllium bronze due to the release of fine phases in its structure [6, 7]. This process improves the hardness, strength properties and wear resistance of the alloy, which is especially important for elements subjected to significant loads. However, further strengthening of properties can be achieved by additional plastic deformation after aging [7]. This combined treatment allows not only to increase the mechanical characteristics but also to improve the isotropy of the material, which expands its capabilities in difficult operating conditions. Hardening is an effective method for changing the microstructure of beryllium bronze, which achieves a more uniform phase distribution and reduces residual stresses [8]. Sharp cooling after heating at high temperatures increases strength and decreases ductility, making the alloy more resistant to stress. Additional plastic deformation after hardening optimizes material properties by combining high hardness with improved wear resistance. This combined treatment is particularly important for high friction and wear applications [9].

Due to its unique combination of mechanical, corrosion and electrical conductive properties, this material is widely used in the aerospace, electronics, power generation and tooling industries. However, the properties of the alloy are significantly influenced by thermomechanical treatments, which can significantly improve its performance characteristics.

ECAP (equal channel angular pressing) is one of the most effective methods of severe plastic deformation (SPD), allowing to create ultrafine grain structure in materials, including beryllium bronze BrB2. This method, as noted in IPD works, provides multiple shear deformation without changing the macroscopic geometry of the specimen, which makes it unique for industrial applications [1]. It has been reported in the literature that grain refinement to submicron or nanometer scale leads to significant improvement in mechanical properties including hardness, strength and yield strength [2].

The purpose of this work is to study the effect of thermomechanical treatments on the properties of beryllium bronze after ECAP and to analyze the changes in the microstructure of the alloy and its mechanical properties, which will allow to optimize the treatment modes to improve the performance characteristics and expand the areas of application of this material.

Materials and methods of experiments

Beryllium bronze alloy containing 97-98 % copper and about 2 % beryllium was used as a material for the study. In addition to the main components, the composition may contain alloying elements such as nickel (up to 0.5 %), iron, silicon and aluminum (up to 0.15 % each), as well as minor impurities. This alloy is characterized by high strength and wear resistance, excellent spring properties, good antifriction characteristics, as well as medium electrical conductivity and thermal conductivity. In addition, beryllium bronze is extremely ductile in the hardened state, which facilitates machining and forming.

To study the influence of thermomechanical treatment, two types of treatment were chosen to study the change in the properties of beryllium bronze. In the first treatment variant, the samples were subjected to hardening at 800 °C and aging process at 320 °C for 2 hours, which allows evaluating the effect of temperature influence on the structure and properties of the material. In the second variant, after the aging process, mechanical treatment was additionally carried out to study the effect of plastic deformation on the material already modified by heat treatment. To study the effect of heat treatment on the properties of the alloy, 9 samples with different treatments were prepared. Table shows the treatment parameters of the samples.

Table

Sample processing parameters

Name of samples	Type of treatment	Processing parameter
No. 1	Without treatment	Initial
No. 2	Heat treatment	800 °C (hardening)
No. 3	Heat treatment	320 °C (aging)
No. 4	Mechanical treatment	ECAP (4 passes)
No. 5	Mechanical treatment	ECAP (3 passes)
No. 6	Mechanical treatment	ECAP (2 passes)
No. 7	Mechanical treatment	ECAP (1 passes)
No. 8	Thermo-mechanical treatment	ECAP (4 passes) + Heat treatment (aging)
No. 9	Thermo-mechanical treatment	ECAP (3 passes) + Heat treatment (aging)

All the selected processing modes are aimed at identifying the optimal conditions to improve the mechanical properties and structural characteristics of beryllium bronze.

The samples were preliminarily ground using 100 to 2000 grit sandpaper and polished using diamond paste. Then, to determine the microstructure, the samples were etched using Kroll’s Reagent (100 ml water, 1–3 ml hydrofluoric acid, 2–6 ml nitric acid).

Metallographic analysis methods using Olympus Corporation optical microscopy, OLYMPUS BX53M, (Tokyo, Japan) were used to study the microstructure of beryllium bronze.

X-ray phase analysis. One of the popular methods of studying the structure of metals and alloys is X-ray diffraction analysis (XRD) [10]. The X-ray diffractometer X'PertPRO from “PANalytical” (the Netherlands) using CuKα radiation was used to study the structure-phase composition of the coatings. The samples were prepared according to standard methods, and the diffractograms of all samples were recorded under the same conditions, which allowed a more accurate comparison of the obtained data. Imaging was carried out at the following parameters: tube voltage U = 40 kV; tube current I = 30 mA; exposure time 1 s; imaging step 0.02°, and the investigated area of angles 2θ was from 20° to 90°. The diffractograms were interpreted using the High Score program and PDF-4 database, and quantitative analysis was performed using the Powder Cell computer program.

Mechanical properties were studied using hardness and elasticity tests. Different methods were used to measure hardness, such as the Vickers method using a diamond pyramid on a Metolab 502. Measurement parameters: load 0.025 g, dwell time 10 s. Vickers number (HV) is calculated by the formula:

$$HV = \frac{1.854P}{d_2}. \quad (1)$$

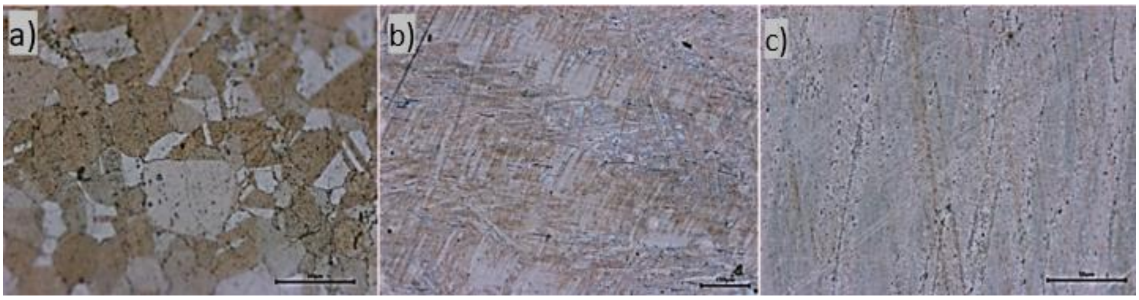
Martens method with hardness and modulus of elasticity investigation using a load-discharge curve. The hardness and modulus of elasticity of the coatings were measured using a FISHER SCOPE HM 2000 system (Helmut Fischer GmbH, Sindelfingen, Germany) controlled with WIN-HCUS software version 7.1. This instrument is designed to evaluate microhardness and other mechanical properties of materials in accordance with the requirements of ISO14577. The waiting time is 10 s and the loading time is 1 N. In order to evaluate the cracking resistance of the coating under constant loads, the cracking initiation rate (CIT) parameter was calculated. This parameter characterizes the change in indentation depth over time under constant load and is calculated as the percentage change in indentation depth versus dwell time. The formula for calculating CIT is as follows:

$$CIT = \frac{h(t) - h_0}{h_0} \cdot 100\ \%. \quad (2)$$

Tribological tests on the “ball-disk” scheme. Tribological tests for sliding friction were carried out on a TRB^3 tribometer (Switzerland Anton Paar Srl,). The tribological properties of the materials were studied using the standard “ball-disk” technique (ASTM G 99). A 3.0 mm diameter ball made of Si_3N_4 coated steel was used as a counterbody. The tests were carried out at a load of 10 N and a linear velocity of 3 cm/s, with a wear curvature radius of 4 mm and a friction length of 100 m. Tribological characteristics were evaluated on the basis of wear intensity and friction coefficient.

Results of the research

Figure 1 shows microstructural analysis of beryllium bronze BrB2, from the three states, revealed significant changes in the structure of the material in the process of heat treatment. In the initial state (Fig. 1*a*) the material has a coarse-grained structure with clear boundaries, which indicates its stable state without significant defects. After quenching (Fig. 1b), the microstructure shows pronounced signs of internal stresses and deformation due to the accumulation of defects resulting from rapid cooling. After aging (Fig. 1*c*), the structure is significantly stabilized: grains are restored, stresses are reduced, and beryllium-rich secondary phases are formed. These changes confirm that the aging process promotes the relaxation of defects, increases the orderliness of the structure and improves the mechanical properties of beryllium bronze BrB2.



a — initial state; *b* — after quenching; *c* — after aging

Figure 1. Microstructure of beryllium bronze BrB2

The results of the analysis (Fig. 2) showed that after quenching (state 2) the structure of beryllium bronze is characterized by a significant level of defects, stresses and reduced crystallite sizes, which is reflected in broad and less intense peaks on the diffractogram. In the aging process (state 3), the separation of beryllium-rich secondary phases is observed, which leads to crystallite growth, a decrease in internal stresses and an increase in the intensity of diffraction peaks. These changes are due to the redistribution of beryllium in the structure, which provides defect relaxation and matrix strengthening. Thus, beryllium bronze BrB2 demonstrates high hardening efficiency due to the formation of an ordered structure and secondary phases during aging, which makes it indispensable in critical applications requiring a combination of strength and resistance to wear.

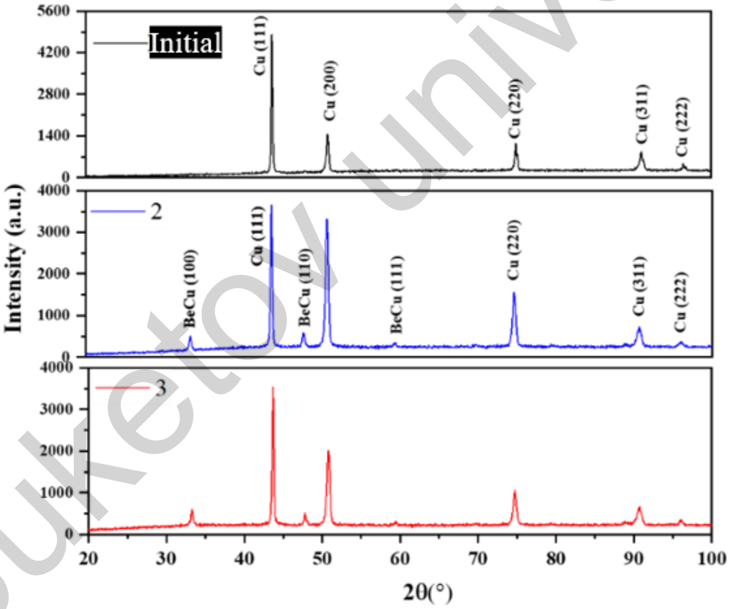


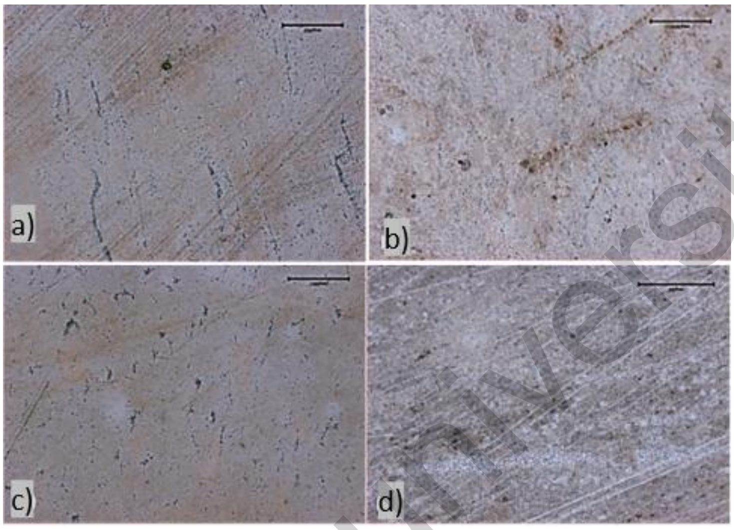
Figure 2. Results of X-ray phase analysis of the studied samples

The conducted studies in Figure 3 showed that after the 1st pass of ECAP, beryllium bronze retains predominantly coarse-grained structure characteristic of the initial stage of plastic deformation, which is consistent with similar data for other materials such as aluminum and copper alloys. At this stage, high-angle grain boundaries begin to form and zones of local accumulation of dislocations begin to nucleate, which is confirmed by studies of deformation processes in metals [4].

After the 2nd pass, active grain refinement and increase in dislocation density are observed, which is associated with intensive shear and stress redistribution in the material. Similar effects have been described in studies based on IPD of aluminum alloys, where after two or three passes the appearance of substructure with low-angle boundaries and initial stabilization of grains were observed [5]. In the case of beryllium bronze, this process leads to an increase in hardness and initial phase stabilization due to the redistribution of beryllium and defects in the structure.

At the third stage (after the 3rd pass), the grains become finer, reaching submicron size, and the structure shows signs of recrystallization. Similar changes are described in the works devoted to copper and its alloys, where the third pass of ECAP promotes the creation of a highly ordered ultrafine — grained structure. For beryllium bronze BrB2, this means that the material acquires optimum properties for mechanical hardening and improved wear resistance.

After the 4th pass, the material structure is fully stabilized, the grains reach nanometer dimensions and defects and internal stresses are virtually absent. This confirms the fundamental theories of IPD, according to which an increase in the number of passes leads to the formation of a stable ultrafine-grained structure with high mechanical characteristics [6]. In addition, for beryllium bronze, improvements in properties such as fatigue limit and corrosion resistance can be expected at this stage, as has been observed for other copper-based alloys.



a — after 1 pass; *b* — after 2 passes; *c* — after 3 passes; *d* — after 4 passes

Figure 3. Microstructure of beryllium bronze BrB2 after ECAP

Thus, in comparison with literature data, the results of ECAP for beryllium bronze BrB2 confirm the general regularities characteristic of materials subjected to severe plastic deformation. The method allows to achieve a unique combination of mechanical and operational properties, making this alloy promising for use in critical structures.

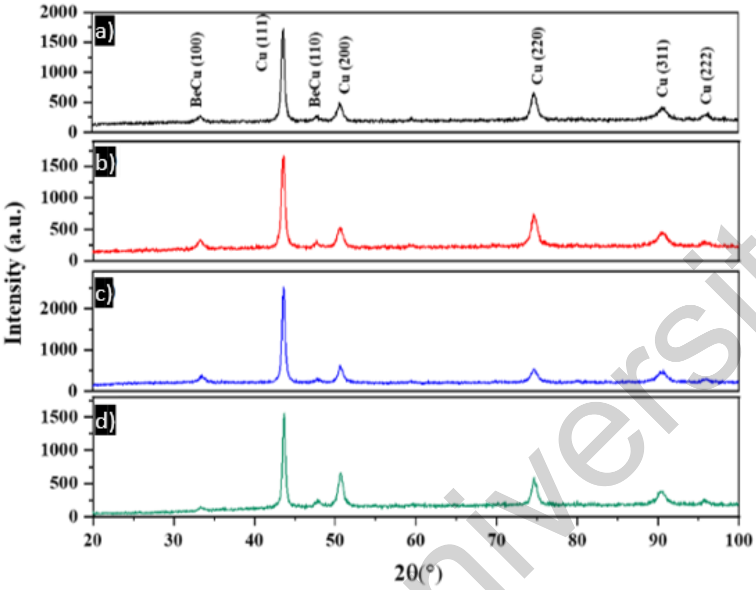
The X-ray diffraction studies of beryllium bronze BrB2 in Figure 4 confirm the influence of ECAP on the evolution of its phase composition and defect structure. After the 1st pass, relatively broad and less intense diffraction peaks are observed, indicating the initial stage of grain refinement and an increase in defect density. This is consistent with literature data, where it is noted that the early stages of severe plastic deformation are accompanied by the formation of a large number of dislocations that begin to localize in the grain structure [11].

At the 2nd pass the peaks become sharper, indicating active redistribution of stresses in the material and further pulverization of the structure. The appearance of substructures with low-angle boundaries and the first signs of recrystallization allows the material to retain high hardness while maintaining plasticity [12]. Besides, it is confirmed by the change of lattice parameters of beryllium bronze, which can be related to the redistribution of beryllium atoms and local stabilization of the phase composition.

After the 3rd pass of ECAP, further ordering of the structure, peak intensity and reduction of line widths are observed. This indicates significant grain refinement and formation of high-angle grain boundaries characteristic of ultrafine-grained materials. Such changes in the structure are the basis for a significant improvement in the mechanical properties of the material, as noted for copper and aluminum based alloys in similar studies [13].

After the 4th pass, the structure stabilizes: the width of peaks on the X-ray image decreases and their intensity reaches the maximum value. This confirms the completion of recrystallization processes, redistribution of internal stresses and formation of a stable ultrafine-grained structure [14]. Similar results for other alloys indicate that after 4-5 passes an optimum balance between mechanical properties such as hardness, strength and ductility is achieved [15].

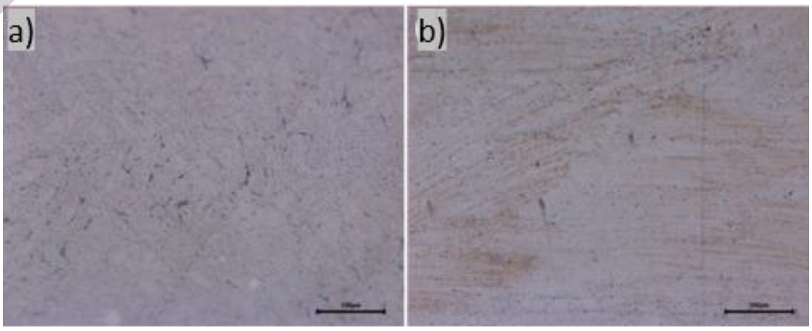
Comparison with literature data shows that BrB2 beryllium bronze exhibits similar trends as other metals subjected to IPD, with the presence of beryllium contributing to the formation of a unique stable structure that enhances the mechanical properties of the alloy. The data obtained during ECAP confirm the promising potential of this method for industrial hardening of beryllium bronze, which makes it suitable for use in critical structures where high strength, hardness and wear resistance are required.



a — after the 1st pass; *b* — after 2 passes; *c* — after 3 passes; *d* — after 4 passes

Figure 4. Radiographs of beryllium bronze BrB2 after ECAP

Figure 5 shows that thermal aging of beryllium bronze BrB2 at 320 °C for 2 hours was carried out on samples that underwent ECAP 1st (*a*) and 2nd (*b*) passes. Microstructural analysis has shown that after aging the sample (*a*), subjected to the 1st pass of ECAP, retains a relatively coarse-grained structure with minimal separations of secondary phases, which is associated with the initial stage of beryllium redistribution and a moderate degree of plastic deformation. Sample (*b*), treated with 2 passes of ECAP, shows more pronounced grain refinement and the presence of secondary phases formed as a result of thermal aging, which is associated with a higher degree of plastic deformation and accumulation of defects after the second pass. These structural changes confirm that thermal aging effectively eliminates defects, redistributes beryllium and improves mechanical properties, especially for samples with more intense pre-plastic deformation. This makes ECAP treatment followed by aging a promising method for increasing the hardness and strength of BrB2 beryllium bronze.



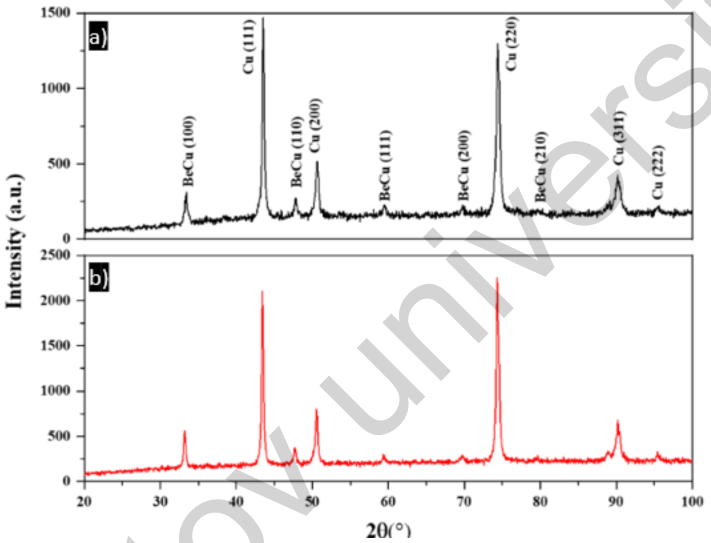
a — sample after 1 ECAP pass; *b* — sample after 2 ECAP passes

Figure 5. Microstructure of beryllium bronze BrB2 after ECAP and thermal aging at 320 °C for 2 hours

The diffractograms of the samples in Figure 6 show significant changes in the width and intensity of the peaks. In the sample after the 1st pass of ECAP (Fig. 6*a*), the peaks are characterized by moderate width and relatively low intensity, which indicates the presence of a high level of defects in the crystal lattice and the initial stages of beryllium redistribution. Thermal aging promotes the separation of secondary phases, but their fraction remains relatively low, which is confirmed by moderate changes in peak intensities.

The sample that underwent 2 passes of ECAP (Fig. 6*b*) shows a marked decrease in peak width and a significant increase in peak intensity after aging. This indicates active release of beryllium-rich secondary phases, as well as a significant decrease in the defectivity of the structure. The observed changes reflect the process of stabilization of the ultrafine-grained structure formed as a result of intense plastic deformation.

Thus, the results of XRD confirm that the increase in the number of passes of ECAP promotes more intensive grain refinement and accumulation of defects, which creates preconditions for the formation of hardening phases in the process of thermal aging. This leads to improvement of mechanical properties of beryllium bronze BrB2, including increase of hardness and strength. The most pronounced changes in phase composition and structure ordering are observed after 2 passes of RCMP with subsequent aging, which makes this treatment mode preferable for improving the performance characteristics of the material.



a — sample after the 1st ECAP pass; *b* — sample after 2 ECAP passes

Figure 6. X-ray phase analysis of beryllium bronze BrB2 after ECAP and thermal aging at 320 °C for 2 hours

In Figure 7, the samples numbered 1, 2 and 3 shows the results of hardness measurements before and after heat treatment. The initial hardness of the BrB2 sample is about 150 HV, which corresponds to the standard state of the material before heat treatment. In this state, the bronze has its initial structure, which has not gone through the over-quenching or aging process. After quenching (Fig. 7 No. 2) at 800 °C, a stable alpha phase with a beryllium-supersaturated structure is formed which exhibits higher hardness compared to the initial state. Hardening helps to strengthen the metal by increasing the density of its crystal lattice, which explains the increase in hardness. The diagram shows that the hardness of this sample is significantly increased (about 200 HV), which confirms the effect of hardening. Aging (Fig. 7 No. 3) at 320 °C improves mechanical properties, especially hardness, due to the separation of different phases from the material matrix. In the case of beryllium bronze, aging promotes the formation of small crystals that strengthen the structure, increasing hardness. Although aging takes place at a lower temperature, it also leads to an increase in hardness of about 200 HV, as can be seen in the diagram.

Thus, the increase in hardness after quenching and aging is explained by changes in the microstructure of the material, such as the formation of harder phases and the strengthening of bonds between atoms. Quenching at 800 °C increases hardness, while aging at 320 °C improves mechanical properties due to the formation of stable phases that strengthen the bronze structure.

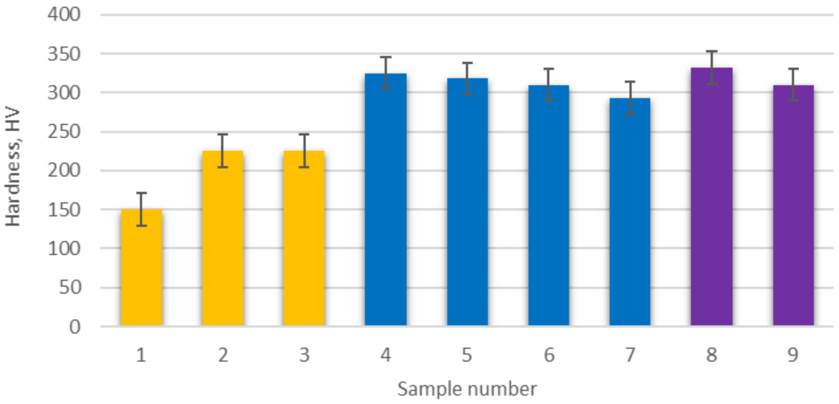


Figure 7. Results of hardness measurement of beryllium bronze BrB2

In Figure 7 from No. 4 to No. 7, the results of hardness measurement after ECAP are shown. The test results show that the hardness of specimen No. 4 is about 320 HV. This is the hardest specimen among the submitted specimens, indicating that the mechanical properties of the material were improved due to the higher number of passes during pressing. Each repeated exposure during the ECAP process improves the structure of the material, increasing its strength and hardness. The hardness of sample No. 5 is about 315 HV. There is a slight decrease in hardness here compared to sample No. 4, which may be due to fewer passes in the pressing process, which does not have the same effect of improving the structure as sample No. 4. The hardness of sample No. 6 is approximately 300 HV. The fewer passes during ECAP, the less pronounced is the improvement in the mechanical properties of the material. This sample has even lower hardness, which may indicate insufficient densification of the material structure. Sample No. 7 has a hardness of about 290 HV, which is the lowest value among the samples presented. The low number of passes during ECAP may not provide a significant improvement in mechanical properties, which is reflected in the lower hardness.

Graphs 8 and 9 in Figure 7 shows comparative data on hardness of two samples of beryllium bronze BrB2 after ECAP and thermal aging at 320 °C for 2 hours. No. 8 sample after 4 passes of ECAP and No. 9 sample after 3 passes of ECAP.

No. 8 specimen was subjected to ECAP with 4 passes and aging at 320 °C. Its hardness is about 330 HV, indicating improved mechanical properties after five passes of pressing as well as aging. This machining process creates a finer-grained structure of the material, which increases its strength and hardness. Sample No. 9 underwent ECAP with 3 passes and was also subjected to aging at 320 °C. Its hardness is lower than that of sample No. 8 and is about 315 HV. This confirms that the number of ECAP passes affects the mechanical properties, and a lower number of passes results in a lower hardness improvement.

Figure 8 shows the results of tribological tests of BrB2 beryllium bronze before and after heat treatment. Graph No. 1 of the sample shows that this sample has a coefficient of friction that varies up to 0.849, with a mean value of 0.734. This means that the source material has moderate friction, but with noticeable fluctuations. These fluctuations may be due to the microstructure of the material, which has not yet been subjected to heat treatments such as quenching or aging.

Graphing for sample No. 2, quenched at 800 °C, the coefficient of friction varies up to 0.936, with an average of 0.771. Quenching at high temperature increased the stability of the material, which is reflected in the slightly higher average friction coefficient value compared to the original sample. Hardening tends to make the material stiffer and stronger, which can lead to an increase in friction.

Graph No. 3 of a sample that underwent aging at 320 °C shows that the coefficient of friction varies up to 0.914, with an average value of 0.764. Aging at a lower temperature increases the hardness and wear resistance of the material, but the average friction coefficient is slightly lower than that of sample No. 2, which may indicate a different type of interaction between the materials during the friction process.

The coefficient of friction of No. 4 sample varies up to 0.855, with a mean value of 0.777 and a standard deviation of 0.031. This sample shows a stable coefficient of friction with noticeable fluctuations, which may be due to the improvement of its structure after five press passes.

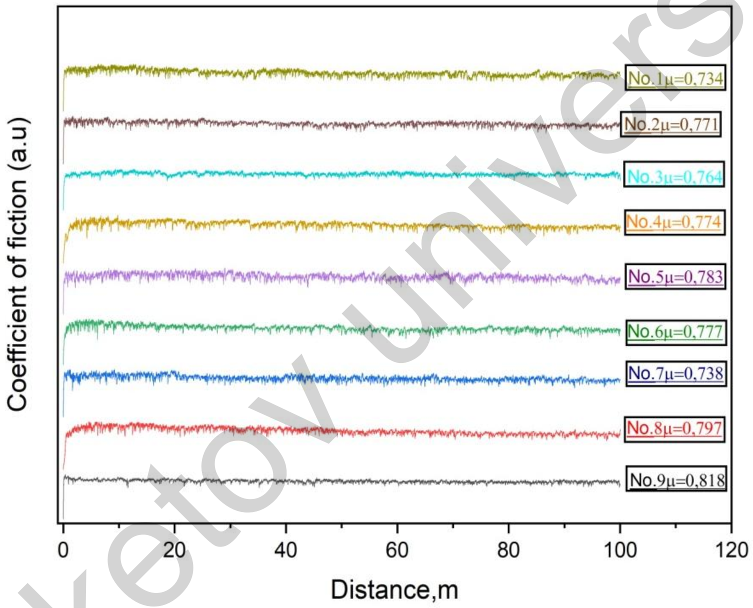
For sample No. 5, the coefficient of friction varies up to 0.896, with a mean of 0.778 and a standard deviation of 0.032. Sample No. 5 has similar values to sample No. 4, but slightly larger variations in the graph. This may indicate the improved mechanical properties associated with ECAP.

The coefficient of friction of sample No. 6 varies up to 0.828, with a mean value of 0.738 and a standard deviation of 0.032. This specimen also shows a stable coefficient of friction, but its value is slightly lower compared to specimens that have undergone more passes, which may indicate less improvement in mechanical properties.

The coefficient of friction for sample No. 7 ranges up to 0.852, with a mean value of 0.738 and a standard deviation of 0.032. This graph is similar to that of sample No. 6, with the same characteristics, indicating stable but not the highest mechanical properties.

The average value of the coefficient of friction for sample No. 8 is 0.797 ± 0.04. This sample showed moderately high variation in the coefficient of friction, with a relatively stable average value. This confirms the improvement in mechanical properties after ECAP and aging, with the material remaining stable under friction.

For sample No. 9, the average value of coefficient of friction is 0.818 ± 0.053. This sample exhibits a higher average value of coefficient of friction (0.818) than sample No. 8. The friction coefficient fluctuations also remain stable, with a slightly larger standard deviation [16].



No. 1 — initial state; *No. 2* — after hardening; *No. 3* — after aging

Figure 8. Results of tribological tests of beryllium bronze BrB2

Thus, ECAP with a higher number of passes (4 and 3) improves the wear resistance and co-friction resistance of the material.

Applications for this work include the manufacture of springs and spring-loaded parts for critical applications, wear-resistant components of various types, and non-sparking tools that are in demand in explosive and aggressive environments. Due to its unique properties, this material is used in electronics, mechanical engineering, aviation and other industries that require a combination of reliability, durability and specific functional characteristics.

Conclusion

The conducted study of the influence of thermomechanical treatment on the properties of beryllium bronze of domestic production allowed obtaining significant results demonstrating the possibilities of improving the mechanical and elastic characteristics of this material. Four main treatment modes were studied: aging, aging followed by plastic deformation, quenching, and quenching followed by plastic deformation. These treatments had a significant effect on the microstructure and mechanical properties of the bronze, including hardness.

Microstructure analysis showed that after thermomechanical treatment, significant changes are observed in the structure of the material: ordered phases are formed, which improve strength properties, and the grain size is reduced, which contributes to increased hardness and wear resistance. The Martens hardness study showed that the maximum hardness was achieved by hardening followed by plastic deformation (sample 4), where the increase was 42.7 % relative to the initial state. Similar trends were observed in Vickers hardness and indentation hardness measurements, where samples subjected to the combined treatment regimes showed the highest values.

Thus, the results of the study show that thermomechanical treatments, especially combined (thermal and subsequent plastic deformation), provide a significant improvement in the mechanical properties of beryllium bronze. These data can be used to optimize machining regimes in industries that require materials with high strength, wear resistance and durability. The obtained results also open perspectives for expansion of application areas of beryllium bronze in critical structures and units operating under conditions of increased mechanical and thermal loads.

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Б.К. Рахадилов, А.Б. Кеңесбеков, Н.М. Магазов,
А.А. Кусайнов, Л.С. Каирбаева, Е.С. Молбосынов

Термомеханикалық өңдеулердің бериллий қоласының қасиеттеріне әсерін оның қолданылуын кеңейту мақсатында зерттеу

Мақала термомеханикалық өңдеулердің бериллий қоласының механикалық және физика-химиялық қасиеттерінің әсерін зерттеуге арналған, яғни қазіргі заманғы технологияларда қолдану аясын кеңейту мақсатында. Қатаю сияқты термомеханикалық өңдеудің әртүрлі әдістері егжей-тегжейлі қарастырылған. Бұл әдістердің қорытпаның микроқұрылымын өзгертуге әсер ету механизмі сипатталған, бұл оның жұмысына тікелей әсер етеді. Алынған нәтижелер бериллий қоласын өнеркәсіпте, авиақұрылыста және басқа да салаларда қолдану салаларын кеңейтуге мүмкіндік береді. Сонымен қатар, негізгі тұжырымдар термомеханикалық өңдеудің озық әдістерін енгізу қоланың физикалық өнімділігін арттыруға ғана емес, бұл материалды аэроғарыш және автомобиль өнеркәсібі сияқты жаңа салаларда қолдануға мүмкіндік беретіндігіне байланысты. Авторлар мақалада материалтану және машина жасау мамандары үшін өте маңызды, өйткені ол бериллий қола бұйымдарын өндіру және пайдалану процестерін жақсартатын жаңа деректер мен ұсыныстарды ұсынған.

Кілт сөздер: БрБ2 бериллий қоласы, термиялық өңдеу, механикалық өңдеу, термомеханикалық өңдеу, тозу, қатаю, материалдың микроқұрылымы, теңарналы бұрыштық престеу (ТАБП)

Б.К. Рахадилов, А.Б. Кенесбеков, Н.М. Магазов,
А.А. Кусайнов, Л.С. Каирбаева, Е.С. Молбосынов

Изучение влияния термомеханической обработки на свойства бериллиевой бронзы с целью расширения области ее применения

В статье исследовано влияние различных режимов термомеханической обработки на структуру и свойства бериллиевой бронзы. Описан механизм воздействия этих методов на модификацию микроструктуры сплава, что напрямую влияет на его эксплуатационные характеристики. Основные выводы сводятся к тому, что термомеханическая обработка повышает физические характеристики бронзы. В статье представлены новые данные и рекомендации, которые помогут улучшить процесс производства и эксплуатации изделий из бериллиевой бронзы, расширить области ее применения в промышленности, авиастроении и других отраслях.

Ключевые слова: бериллиевая бронза, термическая обработка, механическая обработка, термомеханическая обработка, старение, закалка, микроструктура материала, равноканальное угловое прессование (РКУП)

Information about the authors

Rakhadilov, Bauyrzhan— PhD, Associate Professor, Director “PlasmaScience” LLP, Ust-Kamenogorsk, Kazakhstan; e-mail: rakhadilovb@mail.ru; ORCID ID: https://orcid.org/0000-0001-5990-7123

Kengesbekov, Aidar *(corresponding author)* — Postdoctoral fellow, “PlasmaScience” LLP, Ust-Kamenogorsk, Kazakhstan; e-mail: aidar.94.01@mail.ru; ORCID ID: https://orcid.org/0000-0002-5630-9467

Magazov, Nurtoleu— Researcher of the Scientific Center “Protective and Functional Coatings”, Ust-Kamenogorsk, Kazakhstan; e-mail: magazovn@gmail.com; ORCID ID: https://orcid.org/0000-0002-9941-9199

Kussainov Arystanbek — Doctoral student, D. Serikbayev East Kazakhstan Technical University, Ust-Kamenogorsk, Kazakhstan; e-mail: arys20055@gmail.com; ORCID ID: https://orcid.org/0000-0003-4623-4681

Kairbaeva Limara — Student, D. Serikbayev East Kazakhstan Technical University, Ust-Kamenogorsk, Ust-Kamenogorsk, Kazakhstan; e-mail: limaralkairbaeva52@gmail.com; ORCID ID: https://orcid.org/0009-0001-6091-1071

Molbosynov Yermakhan — Student, D. Serikbayev East Kazakhstan Technical University, Ust-Kamenogorsk, Ust-Kamenogorsk, Kazakhstan; e-mail: molbossynov.ye@edu.ektu.kz; ORCID ID: https://orcid.org/0009-0009-0578-6544