https://doi.org/10.53360/2788-7995-2025-2(18)-51

IRSTI: 53.39.01

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EFFECT OF MECHANOACTIVATION ON WC ALLOYS

Abstract: *This paper presents an overview of studies aimed at obtaining tungsten carbide alloys with preliminary mechanical activation (MA). MA is widely used in the field of materials science and is aimed at changing the physical and mechanical properties of materials in order to increase the activity of their reaction during research. In this regard, the main attention in this article is focused on the study of the effect of mechanical activation on tungsten carbide (WC) mixtures. WC-based hard alloys are used in various industrial conditions due to their excellent mechanical properties and outstanding wear resistance in combination with high strength and heat resistance, moreover, more than half of the production of WC-based hard alloys is associated with the manufacture of cutting tools. The article also presents complex types of mechanical activation used in various studies. And also considered the effect of the types of mechanical activation of mixtures on the physical and mechanical properties of the obtained alloys. An analysis of the optimal conditions for powder consolidation by spark-plasma sintering (SPS) is carried out, which allows achieving high density and strength of materials.*

Key words: *mechanical activation, mechanical activation time, tungsten carbide, activation methods, mechanical properties, microstructure.*

Introduction

WC is one of the most well-known components for the production of hard alloys in industry [1]. In the case of using mixtures based on this composition for the purpose of manufacturing cutting tools, single-phase samples are of the greatest value, since they are distinguished by their high thermal stability, in contrast to multiphase samples. Therefore, in order to avoid the emergence of a multiphase component, preliminary mechanical activation of the powder is required.

Mechanical activation is the activation of solids by mechanical processing. This occurs when the rate of accumulation of defects exceeds the rate of their disappearance. This is implemented in the so-called energy-loaded devices: centrifugal, planetary and jet mills, disintegrators, etc., where high frequency and force of mechanical action are combined [2, 3]. As a result of MA of powder compositions, active phase transformations occur in them, which lead to the formation of solid solutions and various intermediate compounds that provide dispersion and disperse hardening of the materials included in the composition. Such removal of powder coatings from the equilibrium state causes their unusual properties [4-6]. As the distance from the equilibrium state increases, the number of parameters determining the state of the system increases, due to which the diversity of structures realized in the material expands, and, consequently, its properties. The structures formed under highly nonequilibrium conditions are stable, therefore a more thorough study of the evolution of the particle structure during mechanical activation of multicomponent mixtures is necessary [7]. Most mechanical activations are carried out using mills, due to the fact that the mill is one of the most common devices, and the experiment with it is distinguished by its simplicity.

The main objective of grinding is to obtain the maximum powder surface with minimum energy expenditure, while the objective of activation is to accumulate energy in crystals in the form of defects or other changes in the solid substance, which would reduce the activation energy of the subsequent chemical transformation of the substance [8, 9]. Mixing tungsten oxide with soot in ball mills was described in textbooks of the last century as a classic method for obtaining tungsten carbide. After mixing, the resulting mixture is loaded into carbidization furnaces, where a chemical reaction of tungsten carbide synthesis occurs in a hydrogen atmosphere [10-12]. Then the synthesized tungsten carbide powder is ground in ball mills, the batches are coarsened and then the material is used to obtain a hard alloy. In all the above methods and techniques using planetary ball mills, an improvement in the properties of the synthesized material is noted due to an increase in the homogeneity of the mixture and the resulting average particle sizes of less than 100 nm, and in some cases less than 40 nm [13]. In addition to mechanical activation, there are other methods of activating materials, such as physical, chemical, thermal and complex, which combines two or more of the above methods.

The aim of the present work is to study the influence of different types of mechanical activation on the microstructure, mechanical properties and phase composition of tungsten carbide (WC) based alloys.

Mechanochemical synthesis

Mechanochemical activation is currently successfully used to intensify technological processes in the construction, food, pharmaceutical, oil and fat, chemical and other industries. Mechanochemical activation is the acceleration or increase in the efficiency of chemical and physicochemical processes under mechanical action [14]. The process of high-temperature mechanochemical synthesis (MCS) was carried out in the work of Onishchenko and Reva [15] in a specially designed experimental setup, and WC synthesis was carried out according to the reaction given in the study of Yagofarov [16]:

$$WO_3 + 3Mg + C \rightarrow WC + 3MgO.$$

The work showed that increasing the amount of polymethyl methacrylate (PMMA) in the reaction to 3% led to a decrease in the content of the W_2C phase. The synthesized powders had a high tendency to consolidation. And at a lower content of PMMA in the synthesized powder, the W_2C phase is present. And also the complete transition of the composition from W_2C to WC can be affected by increasing the reaction conditions during synthesis using molten salt, as in the work of Yang [17], combining mechanical alloying with a chemical reaction in the liquid phase: the final products were characterized by a particle size of 300 to 500 nm, which indicates the successful synthesis of nanostructured materials. And also in the study it was noted that the aggregation of particles was significant.

Tungsten carbide powders (WC and W_2C) can also be synthesized from WCl_6 and Na_2CO_3 by MCS [18]. This study by Aytekin showed that the addition of stoichiometric or 50 wt.% excess magnesium leads to the formation of both WC and W_2C, while excess Na_2CO_3 destroys WCl_6 and WO_2Cl_2, forming only the W_2C, WC and W phases.

Ultrasonic mechanical activation

Ultrasonic mechanical allows for the mechanical activation process to be carried out in a short period of time, to eliminate undesirable pollution phenomena, to obtain finely dispersed and even nanocrystalline powders with a high proportion of the required fraction [19]. The subsequent use of such powders will allow in the future to produce electroceramics with improved properties [20]. By now, it has been well established that ultrasonic treatment (UST) is one of the highly effective methods for modifying the microstructure and mechanical properties of materials [21-23].

The works of Shute and his colleagues [24] are well known, in which ultrasonic activation of powders occurs in a liquid under the action of its shock waves and microcurrents that arise when cavitation bubbles collapse, as well as as a result of mutual collisions of particles during their intense chaotic motion.

Rubanik conducted a study [25] with the aim of clarifying the patterns of changes in composite powders after ultrasonic mechanical activation and determining the possibility of obtaining homogeneous materials with high mechanical properties using such treatment by hot isostatic pressing. The study revealed that after ultrasonic treatment of Co_3O_4 powder, the number of smaller particles increases, while the average particle size remains the same (Fig. 1).

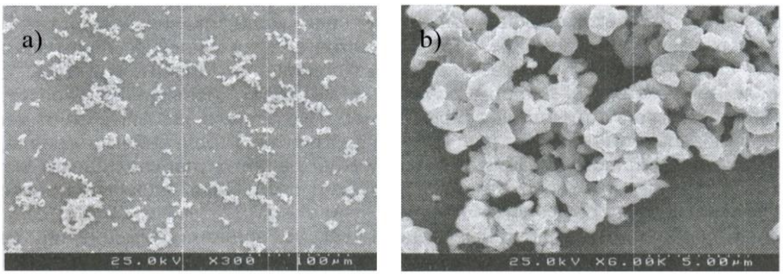

Fig. 1 – Micrographs of Co3O4 powder after ultrasonic treatment: lens ×300 (a) and lens ×600 (b)

In aluminum powders after ultrasonic treatment, in addition to changing the size of the agglomerates, the particle size itself also became smaller (Fig. 2). After ultrasonic treatment, the agglomerates in tungsten and aluminum powders are crushed, as a result, the concentration of smaller agglomerates increases.

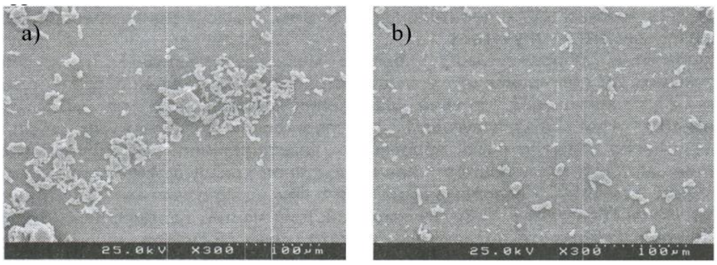

Fig. 2 – Micrographs of aluminum powder before (a) and after ultrasonic treatment (b) [25]

Analysis of X-ray patterns and histograms of particle size distribution of the powders under study showed that intensive ultrasonic action allows for grinding agglomerates and, to a small extent, particles. At the same time, no significant changes were detected in the X-ray patterns of the powders under study. It can be concluded that the optimal mode of ultrasonic treatment is cavitation mode at elevated hydrostatic pressures [25].

Mechanical thermal treatment

The essence of mechanothermal treatment is the long-term grinding of reagents in a ball mill in an inert atmosphere at a temperature at which the surface of the reacting particles is constantly renewed, and the reaction rate is less dependent on the diffusion of the reacting components to each other [26]. However, thermal annealing is necessary after the mechanothermal activation stage to impart the required crystalline structure, which leads to increased energy consumption [27, 28].

The work of Bazhenov and Kurlov [29] presents several important conclusions concerning the synthesis of WC alloys by solid-state methods: the study showed that mechanical activation of a mixture of pure tungsten (W) and carbon (C) in the temperature range from 1000 to 1200 ℃ significantly affects the synthesis process; the results showed that, although single-phase carbon is formed during the synthesis, the final product contains an excess of free carbon; with mechanical activation, the average grain size of the synthesized WC was smaller.

Focusing on the formation of the ternary carbide CoWC through a process called mechanically activated solid-state reaction, a study was conducted by Morgan [30]. This involved milling powder mixtures of cobalt (Co), tungsten (W), and carbon (C) at specific molar ratios and then heating them at high temperatures. The optimum molar ratio to achieve single-phase CoWC was found to be Co/W/C = 7/7/2. When this mixture was milled for 4 hours and heated to 1100 ℃, CoWC was successfully formed although formation began at a relatively low temperature of 800 °C. Overall, these findings suggest that mechanical activation combined with controlled heating can effectively form ternary carbides at lower temperatures, which may impact the synthesis of other complex materials.

Nanosized WC particles can also be synthesized by heating a mechanically activated mixture of WO_3 and graphite under vacuum at different temperatures [31]. It was found that mechanical activation of the WO_3-C powder mixture alone did not result in the formation of the WC phase. However, heating the mixture at 1250 ℃ for 2h resulted in the formation of WC nanoparticles. This means that a certain temperature is crucial for the successful conversion of WO_3 to WC. The addition of KCl to the mixture resulted in the formation of fine and uniform WC particles. In contrast, the presence of nickel promoted the growth of WC particles, suggesting that these additives play an important role in regulating the morphology and size of the nanoparticles. The obtained results highlight the importance of temperature and additives in the synthesis process and provide insights into how to optimize the conditions for obtaining high-quality tungsten carbide nanoparticles. The synthesis of nanostructured WC powders using a two-step process involving mechanical activation followed by thermal activation was also reported by Calderon [32]. The synthesized nanostructured WC powders after sintering formed fine microstructures required to improve the mechanical properties of WC-based solid materials. This improvement was attributed to the successful synthesis process and careful selection of milling parameters and carbon source. Thus, the results of the study highlight the importance of both mechanical activation and carbon source selection in the synthesis of nanostructured WC powders, which are critical for improving the mechanical properties of solid materials.

Mechanical activation followed by thermal activation at temperatures up to 1100 ℃ is also applicable for the synthesis of WC powders using different carbon sources (graphite and carbon black) and different atmospheres (Ar, Ar-50H_2, Ar-10CO) [33]. As a result, single-phase WC powders with grain sizes less than 200 nm were obtained. Ultimately, the WC synthesis was completed at 1100 ℃ in Ar and Ar-10CO atmospheres, with carbon black proving to be more effective than graphite in hydrogen atmospheres.

Mechanical activation of WC-based powders

According to the results of the study by Ozolin and Sokolov [34] concerning the effect of mechanical activation of tungsten powder on the structure and properties of sintered Sn-Cu-Co-W materials, it can be noted that the presence of tungsten nanoparticles significantly affects the dissolution and precipitation of cobalt during liquid-phase sintering of Sn-Cu-Co-W powder material; the sintered Sn-Cu-Co-W material containing mechanically activated tungsten had higher hardness values in the range from 105 to 107 HRB.

By means of mechanical activation in a planetary ball mill, Buravlev et al. carried out work [35] with a mixture of WC – 4 wt. % TiC – 3 wt. % TaC – 12 wt. % Co weighing 50 g. Activation was carried out at a rotation speed of 700 rpm for 10 cycles, each of which consisted of 15 minutes of grinding and 15 minutes of cooling the grinding cup. Then the material was pressed using the SPS technology at different temperatures: 1000 ℃, 1100 ℃, 1150 ℃, 1200 ℃. As a result of mechanical activation, the powder showed a significant shift in the distribution of particle sizes towards smaller sizes with a decrease in the average particle size to 2 μm (Fig. 3).

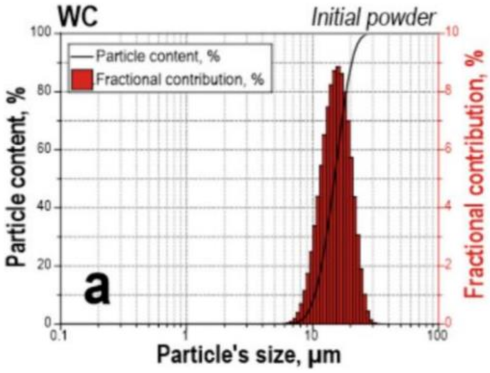

Fig. 3 – Distribution of particle sizes in the original WC powder [35]

X-ray diffraction analysis did not reveal any phase transformation or new formation in the activated powder mixture (Fig. 4).

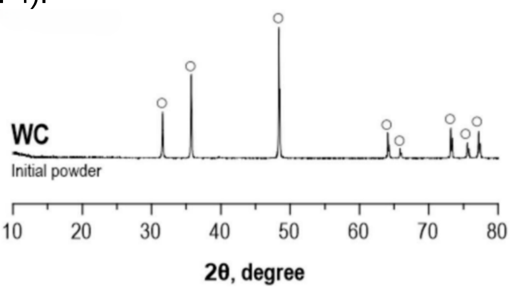

Fig. 4 – Phase composition of the initial powder [35]

Buravlev and his colleagues found that preliminary MA in a planetary mill contributed to the grinding of agglomerates and the sizes of the particles themselves, which intensified the compaction process in the subsequent consolidation of the powder by the SPS method. They also derived the optimal sintering temperature for the best homogeneity and density: 1200℃. Upon completion of the work, the following results were achieved: relative density - 99.99%; hardness, HV30 – 1623.2; bending strength – 1125.1 MPa. In the work of Silva [36], aimed at studying the WC-FeNi alloy as an alternative to the WC-Co alloy, MA was also carried out followed by SPS. The mass ratio of balls to powder during MA was 10:1. The authors of the work claim that the analysis of the obtained WC-

FeNi alloy showed a good distribution of WC grains in its microstructure without the formation of brittle η-phases with a carbon deficiency. The results of the obtained alloy were the best at a temperature of 1300℃: hardness – 1933 HV; density – 99%; fracture toughness – 11 MPa m 0.5. High-energy MA followed by SPS was also mentioned in the work of Chuvildeev [37], devoted to the mechanical properties and structure of W-Ni-Fe and W-Ni-Fe-Co alloys, and it was concluded that the combination made it possible to obtain nanostructured tungsten alloys with exceptional mechanical properties (an increase in macroelasticity from 230 MPa to 635 MPa), which makes them suitable for various complex applications. As a result, the alloys obtained in the above-mentioned works had higher homogeneity, hardness and density than those obtained in other works at the same sintering temperatures, precisely due to the preliminary mechanical activation, due to which the WC binder component was crushed.

Due to mechanical activation of the powder mixture (W+C) in a planetary ball mill, it was possible to synthesize single-phase WC (Fig. 5) in a vacuum at a temperature of 1200 cm℃ with the following characteristics: Ctotal = 6.16% by weight, Cfree – not detected; Dcp = 0.3 μm, Dmin = 0.2 μm, Dmax = 0.7 μm. From a powder mixture of similar composition without mechanical activation and under the same synthesis conditions, a multiphase sample was obtained containing WC, W2C and W [38].

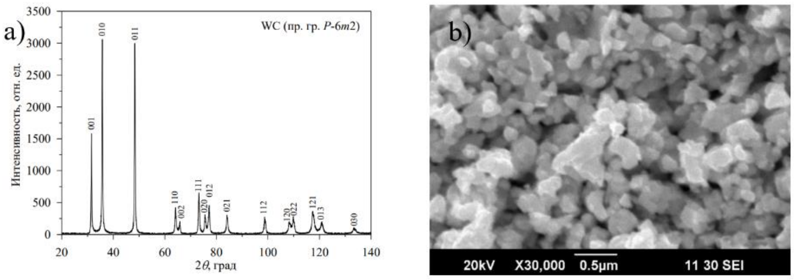

Fig. 5 – X-ray diffraction pattern (a) and SEM image (b) of WC powder synthesized in vacuum at 1200°C from a mechanically activated powder mixture of W and C (carbon black) [38]

The conditions of the mechanical activation certainly have an impact on the final results of the product. For example, the time of the mechanical activation directly affects the density and microstructure of the tungsten alloy, which was revealed in the work of Evstratov et al. [39], in which W-Cu powder composites were studied and the following results were obtained: the maximum density of the mixture was achieved after 5 minutes of mechanical activation, but increasing the time beyond this time led to a decrease in density due to excessive grinding and destruction of agglomerates; the average particle size of the powder, which was previously 4 μm, decreased to 100-400 nm as the mechanical activation time increased to 10 minutes; the distribution of copper particles improved as the activation time increased, which positively affected the strength of the composite. The study showed that although a 5-minute activation time can optimize the density and compaction of the W-Cu composite, a longer activation time can improve the distribution of copper particles and ultimately affect the mechanical strength of the material.

The influence of mechanical activation time on the structure and mechanical properties was also noted in the work of Abdulmenova and Kulkov [40]. Understanding these relationships is of particular importance for optimizing the production processes of heavy tungsten alloys, which are used in various industrial applications. The study by Chuvil'deev [41] found that as the mechanical activation time of WC-based powder increases from 10 to 300 seconds, structural changes in the powder become more pronounced, leading to an increase in the content of amorphous matter and a decrease in particle size, which facilitates subsequent sintering processes. Thus, the study shows that mechanical activation significantly affects the properties of WC-based powder, expanding its application possibilities in sintering hard alloys by changing the phase composition, particle size, and dislocation density. The study by Abdulmenova and her colleagues [42] showed that the average size of agglomerated particles was significantly reduced from 350 μm to 15 μm after 300 seconds of mechanical activation, and the presence of Co_3W_3C carbide phase was also detected, indicating that long-term mechanical activation can lead to the formation of specific phases that can improve the performance of cemented carbides. It was noted that mechanical activation can improve the physical and mechanical properties as well as slow down the grain growth, especially when the processing is performed for a certain period of time from 60 to 100 seconds. In the study by Lee and his colleagues [43], in which MA was carried out by mechanical milling (MM), WC-8Co-2Al cemented carbide alloy was successfully manufactured by SPS. MM was carried out for 55 hours, as a result of which the grain size was reduced from 340 nm to 27 nm, however, with a longer milling, a decrease in the properties and density of sintered carbide alloys was observed. After conducting the SPS of the obtained component in 55 hours of MF, at a peak pulse of 3000 A, the hardness and strength of the material increased to 89 HRA and 1702 MPa, respectively (Table 1).

Table 1 – Effect of MA on WC-based components

Material	Presence and conditions of subsequent sintering	Key Results	MA parameters
WC- TiC-TaC -Co	SPS: 1300 ℃	Optimal parameters (1200 ℃): - Hardness: 1623.2 HV30 - Bending strength: 1125.1 MPa	700 rpm (10 cycles) 15 min. (activation) + 15 min. (activation)
WC -FeNi	SPS	- Hardness: 1933 HV - Fracture toughness: 11 MPa m $^{0.5}$	Ratio of balls:powder :10:1
WC		- Getting single-phase WC - Particle size: 0.2-0.7 microns	
WC-Co		- Agglomerate size: 300 → 15 μm	60-300 sec.
WC-Co-Al	SPS (Pulse: 3000 A)	- Hardness: 89 HRA - Strength: 1702 MPa	55 h. (MF)

Summarizing the results of the above studies, it can be concluded that MA is an integral part of the process of obtaining WC components with the smallest particles and fewer agglomerations, and understanding the relationship between the MA time and the structure and mechanical properties of the material contributes to the production of hard, strong and dense alloys by the SPS method.

Conclusion

Mechanical activation plays an important role in obtaining multicomponent alloys and without it, there is a risk of discrepancy between the expected and obtained results in the study. In this paper, a comprehensive analysis of the effect of mechanical activation on the properties and behavior of tungsten carbide (WC) alloys is carried out. The study confirmed that mechanical activation is a key step in improving the characteristics of powder materials, such as reactivity, structure homogeneity and the possibility of obtaining nanostructured alloys with excellent mechanical properties.

Various approaches to mechanical activation are considered, including mechanochemical, ultrasonic and mechanothermal treatment.

Mechanochemical synthesis allows synthesizing nanostructured materials (300-500 nm), accelerates chemical reactions without using high-temperature processes, and ensures homogeneity of the phase composition (e.g., the transition $W_2C \rightarrow WC$). However, the process carries a risk of powder contamination during long-term processing, which requires extremely precise control of the parameters (time, reagent ratio). MCS is currently successfully used to intensify technological processes in the construction, food, pharmaceutical, oil and fat, chemical and other industries, and is also applicable for the synthesis of ternary carbides (CoWC) for tool steels and the production of WC nanopowders for sintered composites.

Ultrasonic mechanical activation reduces the processing time by 5-10 times, eliminates powder contamination due to processing in a liquid medium, and reduces the size of agglomerates without changing the crystal structure. The disadvantages of such processing include limited effectiveness for highly plastic materials. It is applicable for the preparation of fine Al/W powders for powder metallurgy and modification of oxide powders (Co_3O_4) for catalytic systems.

Mechanothermal treatment can reduce the WC synthesis temperature by 200-300°C and also allows controlling the particle morphology using additives (KCl, Ni). It has high energy consumption in the case of a two-stage process and the risk of forming free carbon during WC synthesis. It is applicable for the synthesis of single-phase WC with grain sizes less than 200 nm in inert atmospheres and the production of W-Cu composites with improved thermal conductivity

Traditional mechanical activation has high energy efficiency and is also capable of reducing the average particle size from 4 μm to 100-400 nm. However, excessive grinding leads to deterioration of properties and can lead to the formation of undesirable phases during long-term activation. Traditional MA is applicable for the production of WC-based composite cutting tools and for the creation of wear-resistant coatings for the aerospace industry, and is also highly efficient for subsequent alloy production by the SPS method.

Thus, the results of the article confirm the importance of the parameters of mechanical activation, among which the time of its implementation plays an important role, as a method of preliminary treatment of WC powders to obtain high-quality materials. Further study of the activation mechanisms and optimization of the process parameters provide opportunities for the development of new generations of hard alloys with unique properties.

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Acknowledgements

This research is funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (grant No. BR24992925).

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ВЛИЯНИЕ МЕХАНОАКТИВАЦИИ НА СПЛАВЫ WC

В настоящей работе представлен обзор исследований, направленных на получение сплавов на основе карбида вольфрама с предварительно проведенной механоактивацией (МА). МА широко применяется в области материаловедения и направлена на изменения физико-механических свойств материалов с целью повышения активности их реакции при проведении исследований. В связи с этим, основное внимание в данной статье направлено на исследование влияния механоактивации на смеси на основе карбида вольфрама (WC). Твердые сплавы на основе WC используются в различных промышленных условиях, благодаря их отличным механическим свойствам и выдающейся износостойкости в сочетании с высокой прочностью и термостойкостью, более того больше половины производства твердых сплавов на основе WC связана с изготовлением режущих инструментов. В статье также приведены комплексные виды механической активации, применяемых в различных исследованиях. А также рассмотрено влияние видов механоактивации смесей и длительности ее проведения на физико-механические свойства полученных сплавов последующими методами синтеза. Проведен анализ оптимальных условий для консолидации порошков методом искро-плазменного спекания (ИПС), что позволяет достигать высокой плотности и прочности материалов.

Ключевые слова: *механоактивация, время МА, WC, методы активации, механические свойства, микроструктура.*

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МЕХАНОАКТИВАЦИЯНЫҢ WC ҚОРЫТПАЛАРЫНА ӘСЕРІ

Бұл мақалада алдын ала механоактивациялау (МА) арқылы вольфрам карбиді негізіндегі қорытпаларды алуға бағытталған зерттеулерге шолу берілген. Механикалық белсендіру материалтану саласында кеңінен қолданылады және зерттеу барысында олардың реакциясының белсенділігін арттыру мақсатында материалдардың физикалық-механикалық қасиеттерін өзгертуге бағытталған. Осыған байланысты, осы мақаланың негізгі бағыты вольфрам карбиді (WC) негізіндегі қоспаларға механикалық белсендіру әсерін зерттеу болып табылады. WC негізіндегі карбидтер олардың тамаша механикалық қасиеттері мен тозуға төзімділігі жоғары беріктігі мен ыстыққа төзімділігі арқасында әртүрлі өнеркәсіптік орталарда қолданылады, сонымен қатар WC негізіндегі карбидтер өндірісінің жартысынан көбі кескіш құралдарды өндірумен байланысты. Мақалада сонымен қатар әртүрлі зерттеулерде қолданылатын механикалық активтендірудің күрделі түрлері келтірілген. Алынған қорытпалардың физикалық-механикалық қасиеттеріне қоспалардың механикалық активтену түрлерінің әсері де қарастырылады. Ұнтақты ұшқынды плазмалық агломерациялау (SPS) арқылы ұнтақты біріктірудің оңтайлы шарттарына талдау жүргізілді, бұл материалдардың жоғары тығыздығы мен беріктігіне қол жеткізуге мүмкіндік береді.

Түйін сөздер: *механикалық белсендіру, МА уақыты, WC, белсендіру әдістері, механикалық қасиеттері, микроқұрылымы.*

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Received 02.05.2025
Revised 03.06.2025
Accepted 04.06.2025

https://doi.org/10.53360/2788-7995-2025-2(18)-52

МРНТИ: 44.31.31

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ИССЛЕДОВАНИЕ ТЕПЛОФИЗИЧЕСКИХ СВОЙСТВ НАНОЖИДКОСТИ AL_2O_3 НА ОСНОВЕ СМЕСИ ЭТИЛЕНГЛИКОЛЯ И ВОДЫ (40:60) ДЛЯ ГЕОТЕРМАЛЬНОГО ПРИМЕНЕНИЯ

Аннотация: *В данной работе представлены результаты экспериментального исследования теплофизических свойств наножидкости Al_2O_3–ЭГ:вода в контексте ее применения в геотермальных тепловых насосах. Эксперимент проводился при температурах от 0 до 10 °C и концентрациях наночастиц 1, 3 и 5 об.%. Измерения показали, что при концентрации 1 об.% теплопроводность увеличивается на 8,2%, при 3 об.% – на 17,4%, а при 5 об.% – на 27% по сравнению с базовым раствором ЭГ:вода (40:60). Однако вязкость при 5 об.% возросла на 45%, что приводит к увеличению гидродинамических потерь. Оптимальная концентрация 3 об.% обеспечивает повышение теплопроводности на 17,4% при росте вязкости всего на 21%, что является компромиссом между эффективностью теплопередачи и насосными затратами. Вычисленный критерий эффективности (PEC) подтверждает, что наилучший баланс достигается при 3 об.% Al_2O_3, где PEC = 0,5. Дальнейшие исследования должны учитывать влияние наночастиц на коррозию, долговременную стабильность и взаимодействие с элементами системы. Полученные результаты могут способствовать разработке более эффективных теплоносителей для геотермального отопления и снижения энергопотребления тепловых насосов.*

Ключевые слова: *геотермальная энергетика, наножидкость, теплопроводность, вязкость, Al_2O_3, этиленгликоль, теплофизические свойства, тепловой насос.*

Введение

Мировое потребление возобновляемой энергии значительно выросло за последние два десятилетие, достигшее объема 90,23 эксаджоулей в 2023 году [1]. Быстрыми темпами растет такой сектор возобновляемой энергетики как геотермальная энергетика, в основе которой лежит утилизация тепла из недр Земли. Количество установленной мощности геотермальных установок возросло с 14,4 ГВт [2] к 2020 году до 16,4 ГВт в 2023 году [3]. Геотермальная энергия как вид экологически чистой энергии имеет потенциал для удовлетворения некоторых основных мировых потребностей в энергии, замены ископаемого топлива и содействия сокращению выбросов парниковых газов [4-6].

Геотермальная энергия – это возобновляемый источник энергии, извлекаемой из внутреннего тепла Земли. Она добывается из подземных резервуаров горячей воды, пара или горячих сухих пород и может использоваться для производства электроэнергии, прямого отопления и промышленных целей. Низкотемпературная геотермальная энергия (низкопотенциальное тепло) относится к теплу, извлекаемому из подземных источников с температурой, как правило, ниже 150° С. Этот тип геотермальной энергии не подходит для традиционной выработки электроэнергии, но широко используется для прямого нагрева. Доля использования низкопотенциального тепла в геотермальной энергетики составляет весомый вклад на уровне 70 % [7, 8].