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Application of Plasticizers Octadecane to Pentatriacontane and Ethylene Glycol in the Manufacture of Metaloceramic Alloys

Boranbay Ratov,[1] Aidar Kuttybayev,[1] Nurbol Tileuberdi,[2,*] Zamanbek Utepov,[5] Madiyar Aliakbar,[1] Arailym Zhanggirkhanova,[1] Oleksandr Pashchenko,[3] Oleksandr Kamyshatskyi,[4] Volodymyr Khomenko,[3] Oleksandr Zaichuk[5] and Askar Seidaliyev[6]

Abstract

The study aimed to investigate the impact of plasticizers on the properties of metal-ceramic hard alloys and develop recommendations for optimizing their composition, concentration, and production process parameters. WC8 alloy powder containing 8% cobalt binder and varying tungsten carbide grain sizes (2.5–8 µm) was used. Plasticizers tested included paraffin and polyethylene glycol (PEG) in concentrations of 1–3%. Powder mixtures were pressed under high pressure and subjected to vacuum-compression sintering. Mechanical properties such as bending strength, hardness, and density were analyzed using standard measurement techniques. Plasticizers improved the flowability of powder mixtures and the quality of pressing. Paraffin at concentrations of 1–2% provided the best results, achieving a bending strength of 2030 MPa, a density of 14.8 g/cm³, and a hardness of 88 HRA. PEG showed lower performance due to increased porosity, especially at concentrations of 3%. Reducing tungsten carbide grain size to 2.5 µm further enhanced the mechanical properties of the alloys. Optimal plasticizer concentrations for sintering hard alloys under vacuum-compression conditions were established for the first time. It was determined that paraffin is more effective in forming a homogeneous material structure compared to PEG. The results can be applied in the production of hard alloys for various industries, including mechanical engineering, metallurgy, aerospace, and defense, ensuring improved product quality and reliability.

Keywords: Hard alloys; Plasticizers; Paraffin; Polyethylene glycol; Vacuum-compression sintering; Mechanical properties.
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1. Introduction

Metal-ceramics or cermets are extremely important materials to produce drilling equipment and in drilling due to their unique properties that combine the advantages of metals and non-metals, such as ceramics and metal carbides. This material forms a heterogeneous composition, which is characterized by high strength, excellent wear resistance, high heat resistance and excellent anti-corrosion properties.[1,2] These characteristics make metal ceramics indispensable in conditions of high mechanical and thermal loads, which often occur during rock drilling or working with solid materials in drilling equipment.[3-6]

Metal-ceramics are used to create tools and parts that must withstand the extreme working conditions typical of drilling processes.[7,8] The high wear resistance and heat resistance of metal-ceramic materials allow them to be used for the manufacture of drilling tools operating at high temperatures and under mechanical loads, ensuring durability and efficiency in difficult operating conditions.[9-14] Metal-ceramics are also used as an anti-friction or protective coating for parts of drilling equipment subjected to significant loads, reducing wear and increasing tool life.[15-18]

The process of manufacturing metal-ceramic materials for drilling equipment often includes the use of powder metallurgy, in particular, the method of pressing and sintering metal and ceramic powders.[19,20] This approach makes it possible to obtain solid materials with high operational

[1] *Department of Geophysics and Seismolog, Satbayev University, 22a Satbayev str., Almaty, 050013, Republic of Kazakhstan*
[2] *Department of Hydrogeology, Engineering and Oil and Gas Geology, Satbayev University, Almaty, 050013, Republic of Kazakhstan*
[3] *Oil and Gas Engineering and Drilling Department, Dnipro University of Technology, Dnipro, 49005, Ukraine*
[4] *Mining equipment plant Tehpostavka LLC, Dnipro, 49000, Ukraine*
[5] *Department of Hydrogeology and Engineering Geology, Ukrainian State University of Science and Technologies, Dnipro, 49010, Ukraine*
[6] *Research and Development, Yessenov University, Aktau, 130000, Republic of Kazakhstan*
**Email:* n.tileuberdi@satbayev.university (N. Tileuberdi)

characteristics, which are necessary to ensure effective work in difficult drilling conditions. A special role in production is played by cemented carbides, which are widely used for the manufacture of drilling tools, as they provide high wear resistance and heat resistance.[21,22]

Metal-ceramic materials can contain such elements as chromium (Cr), nickel (Ni), aluminum (Al), iron (Fe), cobalt (Co), titanium (Ti), zirconium (Zr) and their alloys, which give them excellent mechanical and corrosion properties. In turn, the ceramic phase can include components such as oxides (Al_2O_3, Cr_2O_3, SiO_2, ZrO_2), carbides (WC, SiC, Cr_3C_2, TiC), borides (Cr_2B_2, TiB_2, ZrB_2) and nitrides (TiN), which are also more increases their wear resistance and thermal conductivity, which is especially important for use in drilling conditions.[23-26] The share of the ceramic component in metal ceramics varies depending on its type and can range from 15 to 85% by volume. This allows you to vary the properties of the material depending on the specific requirements for the final product, which is important in the manufacture of drilling tools.[27-32]

Metal ceramics are closely related to powder metallurgy, which is the main method of their production. With the help of powder metallurgy, blanks are obtained, which are made by pressing metal and ceramic powders, followed by their sintering, which makes it possible to obtain high-quality solid materials with the required properties. Metal-ceramic materials are demanded, in cemented carbides, which are widely used for cutting metals, as well as in rock drilling. Production of such materials ensures high wear resistance and durability of tools and parts used in complex technological processes.[33-37]

The process of obtaining metal-ceramic materials by powder metallurgy includes several stages, among which the preparation of powders, pressing, sintering and further processing are important. At each of these stages, it is important to optimize the parameters to achieve the required mechanical and physical characteristics of the final product. In particular, correctly selected sintering conditions and the ratio of metal and ceramic components allow controlling such properties as hardness, wear resistance, heat resistance and anti-corrosion resistance of the material, which is critical for the use of metal ceramics in the drilling industry.[38,39]

Therefore, metal-ceramics are an important material for the drilling industry because they combine the best properties of metals and ceramics to create efficient and durable drilling tools and parts. The development of new methods of production of metal-ceramics and the improvement of their manufacturing technologies open new opportunities for improving the quality and efficiency of drilling equipment, which is important for successful drilling operations in difficult conditions. It also significantly improves drilling efficiency and safety, reducing maintenance costs and equipment wear and tear under extreme loads.[40-43]

1.1 Metal-ceramic hard alloys: characteristics and classification

Metal-ceramic hard alloys are materials that combine high hardness and wear resistance, able to maintain these properties during operation at high temperatures, usually from 900 to 1150 °C. This ensures their effective use in tools and materials subjected to intense mechanical loads and exposure to high temperatures. Such alloys are usually made based on carbides of tungsten, titanium, tantalum and chromium, which are combined with a metallic bond, which is usually cobalt or nickel. The content of cobalt or nickel in the bond varies depending on the required properties of the final material.[44]

Metal-ceramic hard alloys can be classified by chemical composition, among which the following groups are the most common:[45,46]

- Tungsten cobalt hard alloys (WC) are alloys in which the main component is tungsten carbide, and the metallic bond is cobalt. They are characterized by excellent wear resistance and high hardness, which allows them to be used to produce various tools, in particular for processing metals and in conditions of high temperatures.
- Titanium tungsten cobalt hard alloys (TWC) – alloys containing titanium carbide together with tungsten carbide in combination with a cobalt bond. They have improved mechanical properties, such as high strength at extreme temperatures, as well as increased corrosion resistance.
- Titanium tantalum tungsten cobalt hard alloys (TTWC) are more complex alloys containing carbides of titanium, tantalum and tungsten, with a cobalt bond. They are used in cases where extreme wear resistance and heat resistance are required, in particular in the defense and aerospace industries.

The structure of metal-ceramic alloys of the TC group is dominated by tungsten carbide grains, which make up 80-90% of the total mass of the material. These grains have a characteristic awkward shape, often triangular, square or quadrangular, which ensures high hardness and wear resistance of the material. Tungsten carbide grain sizes can vary from 0.5 to 10 μm, but in some cases, in alloys with larger grain sizes, these indicators can reach 30 μm. Increasing the carbide grain size is often used to improve the wear resistance and overall mechanical strength of the material.[47]

1.2 The effect of plasticizers on the process of pressing and sintering

Pressing hard alloy products is a complex technological process that requires the use of plasticizers. These additives have a significant impact on the processes of pressing and sintering, as they facilitate the formation of products, reducing the viscosity of powders and allowing uniform filling of matrices, which ensures high quality of pressed products, reducing the likelihood of defects in the process of forming products.[48] In addition, plasticizers can help improve sintering processes, improving the structure of the material and contributing to its uniform hardening, which positively affects the final properties of the product.[49]

1.3 Metal-ceramic hard alloys: characteristics and classification

Improving the quality of hard alloy products by reducing the heterogeneity of properties is an important task of modern technology. Achieving this allows you to significantly improve the operational characteristics of the finished product, in particular its durability, wear resistance and stability at high temperatures. Improvements in pressing and sintering technology, the use of the latest plasticizers, and control over the dosing and powder formation processes make it possible to obtain materials with more uniform properties, which expands the possibilities of their use in various industries.[50,51]

Sintering of metal-ceramic alloys is a very complex process, which includes several insufficiently studied physicochemical processes that significantly affect the composition, structure and properties of the final product. During this process, changes occur in the chemical composition of the gas medium, in interaction with powder mixtures that include metals and carbides.[52,53] These changes can lead to inhomogeneity of carbon in alloys, which in turn causes sharp fluctuations in the properties of finished products. The biggest problem is related to the uneven distribution of carbon, which causes variations in the operational properties of products made from different batches or even from the same batch of mixture. Solving this problem will significantly increase the stability and quality of product properties, as well as improve their homogeneity within the batch.

2. Materials and methods

The technology for obtaining hard alloy products has its own characteristics, since the starting materials, in particular powders of metal carbides, are characterized by increased hardness, brittleness and a high modulus of elasticity. For the successful pressing of such materials, organic plasticizers are used, which greatly facilitate the forming process. Plasticizers help ensure the necessary fluidity of powders during pressing, which allows you to obtain uniform blanks and avoid defects at the molding stage.[54-59]

Also, the use of organic plasticizers has its own characteristics, which have not been sufficiently studied until now. Plasticizers affect the carbon content in the structure of products, which is critical for ensuring the required mechanical properties after sintering. It is noted that this influence is significant, but has been little studied so far in scientific literature. In domestic and foreign industry, various organic substances are used for plasticizing powder mixtures, including synthetic rubber, paraffin, glycol, camphor, polyvinyl acetate, polyvinyl glycol, polyethylene glycol, as well as resins dissolved in gasoline, acetone, or ether. Each of these plasticizers has its own characteristics of influence on sintering processes and the carbon composition of the alloy.[60-64]

2.1 Development of recommendations for research methods of plasticizers in the production of hard alloys

In the production of hard alloys, it is necessary to choose plasticizers that ensure optimal fluidity of powder mixtures, which allows you to avoid defects during pressing. At the same time, the plasticizer must have good solubility in suitable solvents, such as alcohol, so that it can be introduced at the stage of wet grinding. The ability of the plasticizer to burn out without residues during sintering should also be considered.[65]

Vacuum-compression sintering is the most effective method, as it allows you to maintain high material quality, minimizing defects and preserving the mechanical properties of alloys. It is important to provide precise control over chemical processes and temperature during sintering, which allows obtaining materials with high density and uniform structure.[66]

It is important to test different concentrations of plasticizers to determine their effect on the final properties of hard alloys. The optimal concentration of the plasticizer should be chosen in such a way as to ensure good fluidity of the powder mixture without adversely affecting the hardness and wear resistance of the material.[67-70]

It is advisable to choose a metal-ceramic hard alloy powder with a defined content of cobalt bonds, such as WC8 (Tungsten Carbide with 8% Cobalt (by weight)), as the research material. It is important to use different sizes of tungsten particles to study the influence of grain size on the properties of the final product.

Powder mixtures with plasticizers must be pressed under high pressure to ensure the necessary density of briquettes before sintering. For sintering, it is recommended to use vacuum-compression furnaces, which allow us to achieve maximum control over the processes of removing plasticizers and sintering at high temperatures.[71]

After sintering, a number of tests must be carried out to determine the mechanical properties of carbide products, such as hardness, wear resistance and density. Evaluation of these characteristics allows us to understand how different concentrations of plasticizers affect the final quality of materials.[72-74]

Hard alloys ISO E513, which are widely used in mechanical engineering, metallurgy, aircraft construction, defense industry and other industries, have several main properties that determine their efficiency and quality in use.[75]

In selecting plasticizers for hard alloy production, paraffin ($C_{18}H_{38}$–$C_{35}H_{72}$) and polyethylene glycol (PEG, $C_2H_4(OH)_2$) were prioritized due to their solubility in alcohol, compatibility with wet grinding, and established use in powder metallurgy. However, the literature identifies other potential plasticizers that may offer distinct advantages. For instance, Zhang *et al.*[1] highlight polyvinyl acetate for its lower evaporation temperature, potentially reducing thermal energy demands during sintering, while Yu *et al.*[37] noted that synthetic rubber can minimize carbon residue, enhancing alloy purity. These alternatives suggest that a broader range of plasticizers could be tailored to specific sintering conditions or alloy compositions, warranting further exploration

beyond the scope of paraffin and PEG in this study.

2.2 The main properties of ISO E513 hard alloys

Density is one of the main physical characteristics of hard alloys, which affects their strength and resistance to wear. The high density of the material contributes to better wear resistance, since hard alloys with a higher density are better able to withstand loads and intense friction without significantly reducing their properties.[76] Wear resistance can be approximated by the dependence shown in Eq. (1):

$$Z \propto \rho \cdot \sigma \quad (1)$$

where σ is the strength of the material.

The density can be found using Eq. (2):[77]

$$\rho = \frac{m}{V} \quad (2)$$

where m is the mass of the material and V is the volume.

Hardness is a critical parameter for materials used in high-wear environments, such as cutting tools or abrasive parts.[78-80] Hardness determines the ability of the material to resist mechanical loads, friction and other destructive influences, which is the key to effective work in these conditions.[81] It can be evaluated on the Vickers or Brinell scale through the force F applied to the impression area A in Eq. (3):[82]

$$H = \frac{F}{A} \quad (3)$$

In the context of friction, wear resistance can be estimated through the Archard formula in Eq. (4):[83]

$$V = \frac{K \cdot F \cdot L}{H} \quad (4)$$

where V is the volume of the worn material, K is the wear coefficient, L is the friction length.

Transverse bending strength limit - this characteristic determines the maximum stress a material can withstand during bending without destroying it.[84] For hard alloys, this is an important property because many structures and tools are subjected to bending loads, and the material must maintain its integrity during service.[85-88] It is determined by Eq. (5):

$$\sigma_{bs} = \frac{3 \cdot F \cdot L}{2 \cdot b \cdot h^2} \quad (5)$$

where F is the applied force, L is the distance between the supports, b is the width of the sample, and h is the height of the sample.

Thus, the parameters ρ, H, and σ_{bs} allow to mathematically evaluate the physical properties of hard alloys and predict their behavior in operating conditions.[89-93] Determining the most suitable plasticizers and their concentrations is key to optimizing hard alloy production technology. It is recommended to compare the properties of different plasticizers and choose the optimal conditions for achieving high mechanical strength and wear resistance of the final products. These recommendations make it possible to develop a methodology for researching the influence of plasticizers on the properties of metal-ceramic hard alloys and their application in real production conditions, and the determination of the main properties of ISO E513 hard alloys will allow a comparative analysis of the obtained materials.

3. Results and discussion

At the Techpostavka LTD (Limited Company) enterprise, a series of experiments was conducted on the selection of plasticizers and operating parameters for obtaining hard alloys.

The two most popular materials were chosen as plasticizers - paraffin ($C_{18}H_{38}$ - $C_{35}H_{72}$) and polyethylene glycol ($C_2H_4(OH)_2$) (PEG). These substances dissolve well in alcohol, which allows them to be added during wet grinding of powders in a ball mill. This contributes to the uniform distribution of plasticizers in the mixture and improves the flowability of powder mixtures at the pressing stage.

The study of the influence of plasticizers on the properties of metal-ceramic hard alloy powder WC8, containing 8% cobalt bond, showed the following results. With an increase in the concentration of the plasticizer to 3% by mass, the fluidity of the mixture improved, which simplified its further pressing. At the same time, concentration above 3% does not provide significant advantages and may lead to some negative effects, such as deterioration of the mechanical properties of the finished products. In Fig. 1 photo of hard alloy samples after sintering on a graphite tray is given.

During vacuum compression sintering, at low temperature and pressure, plasticizers are removed from the mixture, leaving a sinterable powder (Fig. 2). Vacuum compression sintering allows to reduce the number of defects, such as porosity and oxidation, which are characteristic of traditional sintering methods. At optimal concentrations of plasticizers of 1-2%, a high density of the material after sintering was



a b c

Fig. 1: Photo of experimental samples: a - after sintering; b and c - polished.

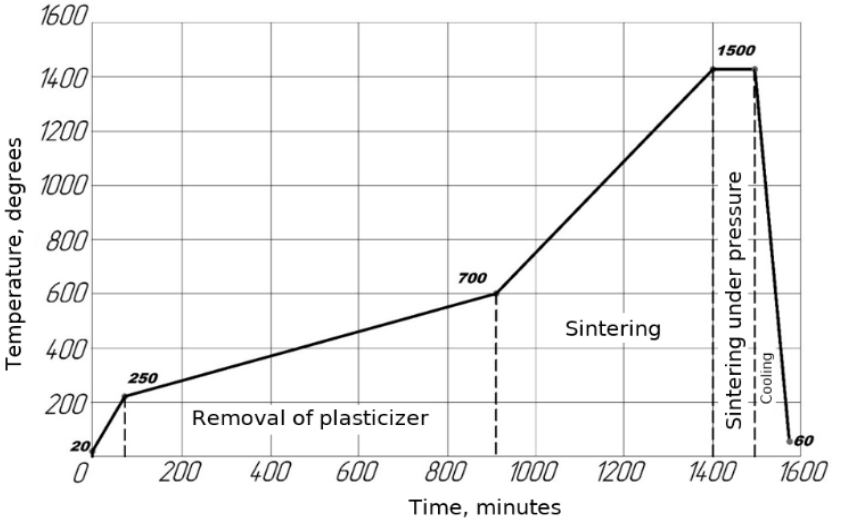


Fig. 2: Mode of operation of the vacuum-compression furnace.

observed. Increasing concentration to 3% also did not significantly degrade the sintering results, but decreasing the concentration to 1% provided the best result in several criteria, including mechanical strength and material homogeneity.

Regarding the grain size of tungsten carbide, it was found that reducing the grain size to 2.5 μm improves mechanical properties such as hardness and wear resistance (Table 1). Smaller grain size allows to form a more uniform structure, which increases the strength of the products (Figs. 3 and 4). An increase in the grain size to 5-8 μm reduced the strength and wear resistance due to the formation of larger pores and defects in the material (Figs. 5 and 6).

The results of studies of the effect of the amount and type of plasticizer on the properties of the WC8 metal-ceramic hard alloy are given in Table 1. Due to the existing porosity in the samples sintered with PEG plasticizer, the sections are presented in Figs. 5 and 6 are shown with a magnification of x160 to provide greater visual clarity. The process of vacuum-compression sintering provides a high level of density and strength of materials, which allows you to achieve the best results even with moderate concentrations of plasticizers. Since the number of oxidation reactions and defects decreases during vacuum sintering, it significantly improves the characteristics of the finished products.

The current study evaluated the effects of tungsten carbide (WC) grain sizes of 2.5 μm and 5–8 μm on the mechanical properties of WC8 metal-ceramic hard alloys, revealing that smaller grains (2.5 μm) enhance bending strength, hardness, and structural uniformity (Table 1, Figs. 3-6). However, this range represents only a subset of potential WC grain sizes relevant to hard alloy applications. For instance, García *et al.*[37] investigated WC grain sizes ranging from 0.5 to 30 μm, demonstrating that submicron grains (<1 μm) can further increase hardness, while coarser grains (>10 μm) may improve wear resistance under specific conditions. The limited scope of particle sizes in our study, constrained by practical relevance to drilling tool manufacturing, may not fully capture the broader particle size effect on alloy performance. This limitation highlights the need for future research to explore a wider spectrum of grain sizes, which could refine our

Table 1: Results of studies on the influence of the amount and type of plasticizer on the properties of the WC8 metal-ceramic hard alloy.

Amount of plasticizers, wt.%	Grain size, μm	Softener	Properties		
			Bending strength limit, MPa	Density, $(kg/m^3)\cdot10^{-3}$	Hardness, HRA
1	up to 2.5	paraffin	2030 ± 10	14.8	88 ± 0.5
		PEG	1930 ± 10	14.6	85 ± 0.5
	5-8	paraffin	1830 ± 10	14.8	88 ± 0.5
		PEG	1730 ± 10	14.6	85 ± 0.5
2	up to 2.5	paraffin	2020 ± 10	14.8	88 ± 0.5
		PEG	1900 ± 10	14.6	85 ± 0.5
	5-8	paraffin	1820 ± 10	14.8	88 ± 0.5
		PEG	1670 ± 10	14.6	85 ± 0.5
3	up to 2.5	paraffin	1990 ± 10	14.8	88 ± 0.5
		PEG	1820 ± 10	14.5	85 ± 0.5
	5-8	paraffin	1780 ± 10	14.8	88 ± 0.5
		PEG	1620 ± 10	14.5	85 ± 0.5

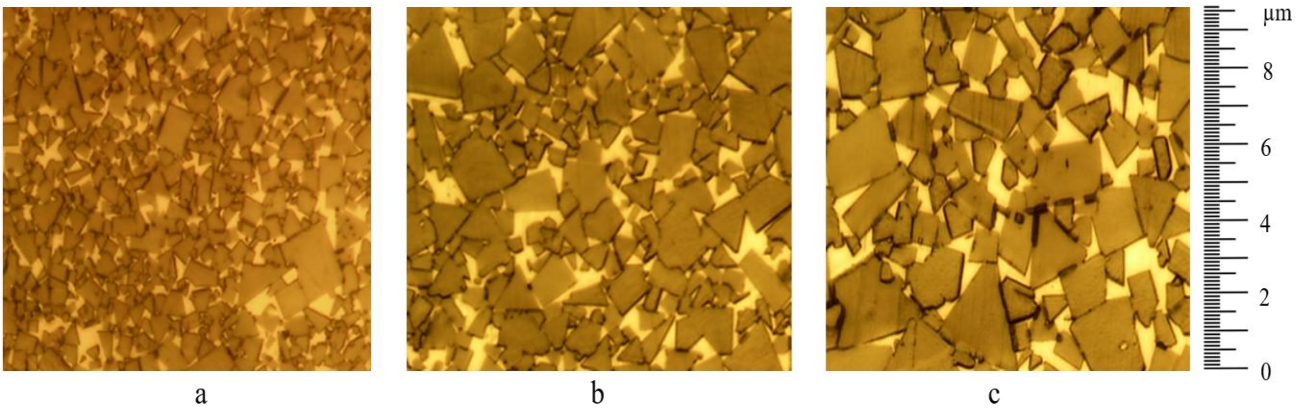


Fig. 3: Obtained structures of hard alloys (magnification x1600, particles up to 2.5 µm): a - plasticizer paraffin 1%, b - plasticizer paraffin 2%, and c - plasticizer paraffin 3%.

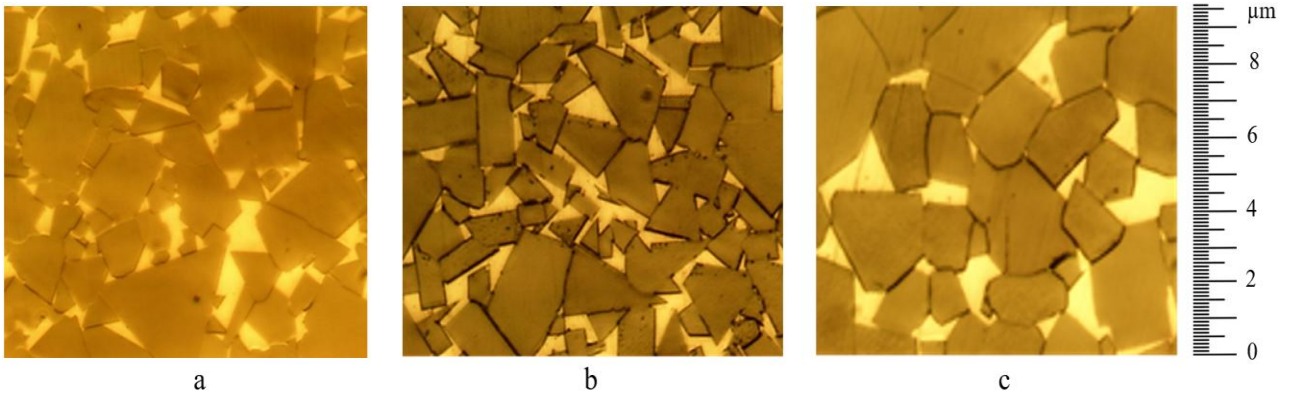


Fig. 4: Obtained structures of hard alloys (magnification x1600, particles 5-8 µm): a - plasticizer paraffin 1%, b - plasticizer paraffin 2%, and c - plasticizer paraffin 3%.

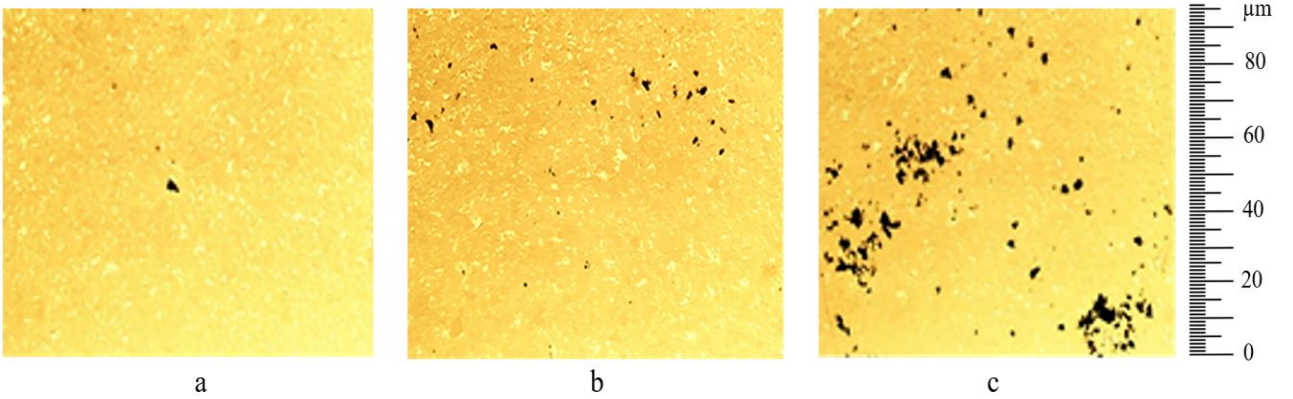


Fig. 5: Obtained structures of hard alloys (magnification x160, up to 2.5 µm, single micropores present): a - plasticizer PEG 1%, b - plasticizer PEG 2%, and c - plasticizer PEG 3%.

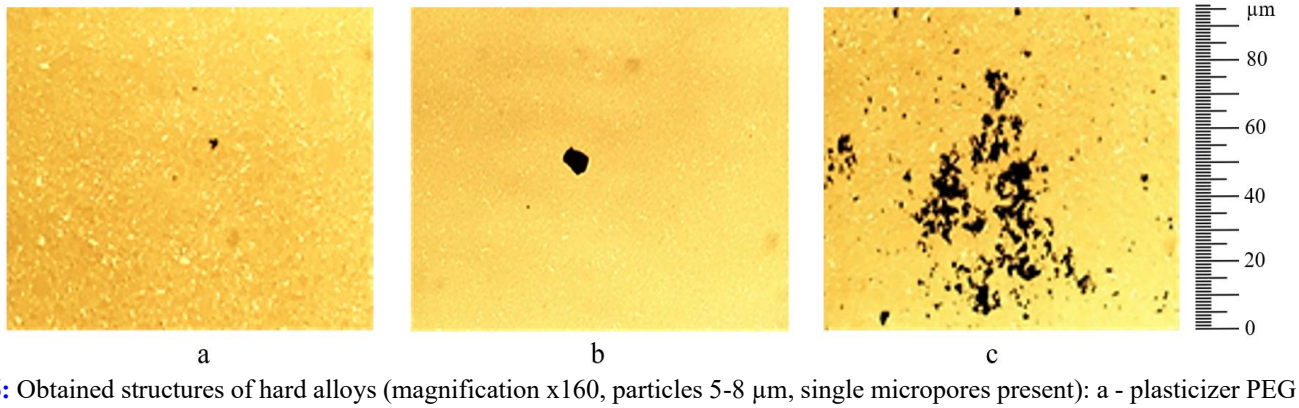


Fig. 6: Obtained structures of hard alloys (magnification x160, particles 5-8 µm, single micropores present): a - plasticizer PEG 1%, b - plasticizer PEG 2%, and c - plasticizer PEG 3%.

understanding of their influence on densification, porosity, and mechanical behavior.

In general, the results show that plasticizers have a positive effect on the pressing and sintering processes of hard alloy materials, but an excessive number of plasticizers can lead to a negative effect on the final properties. Choosing optimal concentration is critical to achieving the best performance of the finished products. Vacuum compression sintering turned out to be an effective method to produce hard alloy materials, which allows for reducing defects and improving mechanical properties with minimal energy consumption.

3.1 Analyzing the results of research on the main properties of ISO E513 hard alloys

Bending strength of the obtained material (MPa) if it were used (Fig. 7(a)):

- Paraffin: Samples plasticized with paraffin show the best flexural strength in 2030 MPa at a concentration of 1% and a grain size of up to 2.5 μm. Paraffin also maintains high strength values at concentrations of 2% and 3%, although a slight decrease in this parameter is observed. In general, paraffin remains the most effective plasticizer for achieving high material strength at the sintering stage.
- PEG: Flexural strength values for PEG-plasticized samples were lower compared to paraffin at all stages of the study. At a concentration of 1% PEG, the strength was 1930 MPa, which is already 100 MPa less than for paraffin. With an increase in the concentration of the plasticizer to 3%, the strength decreased even more, to 1620 MPa. This indicates that PEG is not able to provide the same high bending strength as paraffin.

Density of the obtained material (kg/m³ × 10³) if it was used (Fig. 7(b)):

- Paraffin: The density of the samples remained stable at the level of 14.8 kg/m³ × 10³, which indicates a high quality of sintering when using paraffin, regardless of concentration. There are no significant fluctuations in density, which indicates the efficiency of the sintering process.
- PEG: The density of PEG-plasticized samples was slightly lower compared to paraffin and decreased with increasing plasticizer concentration. At a concentration of 3%, it was 14.5 kg/m³ × 10³, which indicates the presence of porosity in the material. This porosity is probably due to the imperfect removal of PEG during the sintering process, which can negatively affect the mechanical properties of the samples.

Hardness of the obtained material (HRA) if used (Fig. 7(c)):

- Paraffin: The hardness of the plasticized samples with paraffin remained at a stable level of 88 ± 0.5 HRA at all concentrations, indicating good material quality and stability of properties. Paraffin provides high hardness indicators, which is important for wear resistance and durability of the material.
- PEG: The hardness for the PEG plasticized samples remained constant at 85 ± 0.5 HRA, which is lower than that for paraffin. This decrease in hardness can be explained by the presence of porosity in the material, which is the result of reduced heat resistance and poor PEG removal during sintering.

Thus, paraffin showed the best flexural strength, density and hardness, especially at concentrations of 1–2%. This makes it the best choice for plasticizing in hard alloy manufacturing processes. All indicators of the material remain stable and high, which confirms the effectiveness of paraffin as a plasticizer for obtaining high-quality hard alloys.

PEG turned out to be a less effective plasticizer compared to paraffin. The drop in density and hardness in samples plasticized by PEG is due to the formation of porosity, which increases with the increase in the concentration of the plasticizer (Fig. 8). This indicates that PEG has a less stable effect on the physical and mechanical properties of the material, which can lead to a decrease in the wear resistance and strength of the final products.

To further elucidate the trends observed in Table 1 and Figs. 3-6, additional visualizations were developed. Figs. 8(b) and (c) illustrate the relationship between porosity (qualitatively assessed from Figs. 5 and 6) and mechanical properties for PEG samples, showing a clear decline in strength and hardness with increasing porosity at higher concentrations. Fig. 9 presents a bar chart comparing bending strength, density, and hardness across plasticizer concentrations (1%, 2%, and 3%) and grain sizes (2.5 μm vs. 5–8 μm) for both paraffin and PEG, consolidating the data from Table 1. This highlights paraffin's consistent superiority, with bending strength peaking at 2030 MPa (1%, 2.5 μm) compared to PEG's 1620 MPa (3%, 5–8 μm). These figures complement the line graphs in Fig. 7 and microstructural images, offering a clearer visual representation of how plasticizer type, concentration, and grain size influence alloy performance.

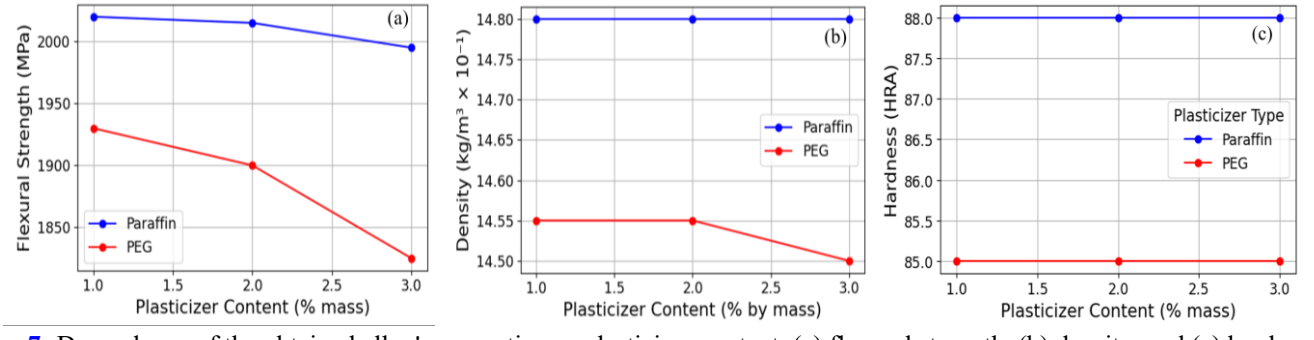


Fig. 7: Dependence of the obtained alloy's properties on plasticizer content: (a) flexural strength, (b) density, and (c) hardness.

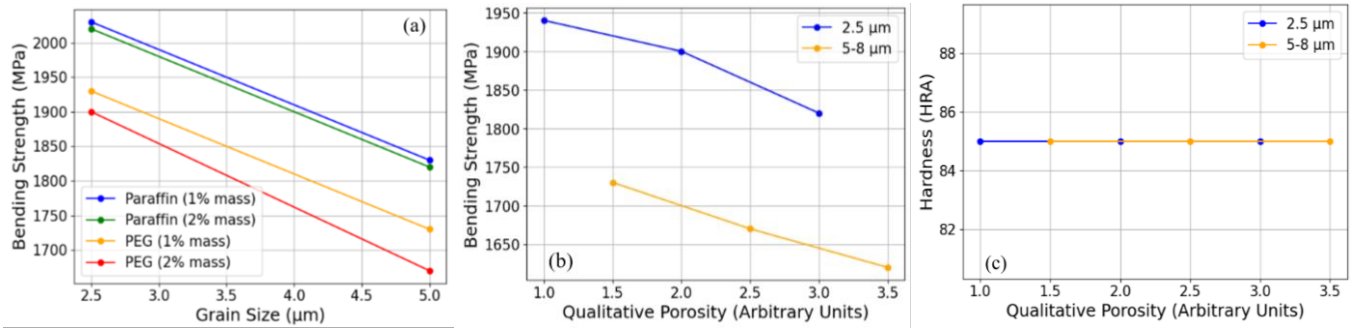


Fig. 8: Mechanical properties of alloy: (a) the effect of grain size on the bending strength, (b) the effect of porosity on the bending strength, and (c) the effect of porosity on the hardness.

The analysis of the results of the study of the properties of hard alloys ISO E513 showed that paraffin is the most effective plasticizer for ensuring high mechanical characteristics. At a concentration of 1% and a grain size of up to 2.5 μm, the material plasticized with paraffin showed a maximum flexural strength of 2030 MPa, maintaining high values even at concentrations of 2–3%. The density of the paraffin-coated samples remained stable at 14.8 kg/m³ × 10³ and the hardness at 88 ± 0.5 HRA, indicating good sintering and no porosity. In samples plasticized with PEG, a decrease in strength (up to 1620 MPa at a concentration of 3%), density (up to 14.5 kg/m³ × 10³) and hardness (85 ± 0.5 HRA) was observed, which is explained by the formation of porosity due to incomplete removal of PEG during sintering. In general, paraffin provides stable and high physical and mechanical properties, which makes it the optimal choice to produce hard alloy materials.

The use of paraffin as a plasticizer in this study offers several distinct advantages over PEG and approaches reported in the literature. First, the 12.8% higher bending strength compared to Ratov *et al*.[12] and 6.8% higher than Yu *et al*.[38] demonstrates that paraffin enables the production of hard alloys with superior mechanical strength, making them more suitable for high-load applications like drilling in challenging geological conditions. Second, the 1.4–2.8% higher density compared to De Medeiros Tavares *et al*.[21] and Ratov *et al*.[19] indicates a more effective sintering process, reducing porosity and enhancing the material's structural integrity. Finally, the 1.1–2.3% higher hardness compared to Ratov *et al*.[8] and Yu *et al*.[38] underscores paraffin's ability to produce harder, more wear-resistant materials, a critical factor for extending the service life of drilling tools. Unlike PEG, which shows a performance decline with increasing concentration due to porosity (Figs. 5, 6, 8(b) and 8(c)), paraffin maintains stability across 1–3% concentrations, aligning with findings by Zhang *et al*.,[14] who found that uniform particle distribution enhances mechanical properties. This consistency and superior performance position paraffin as a competitive choice

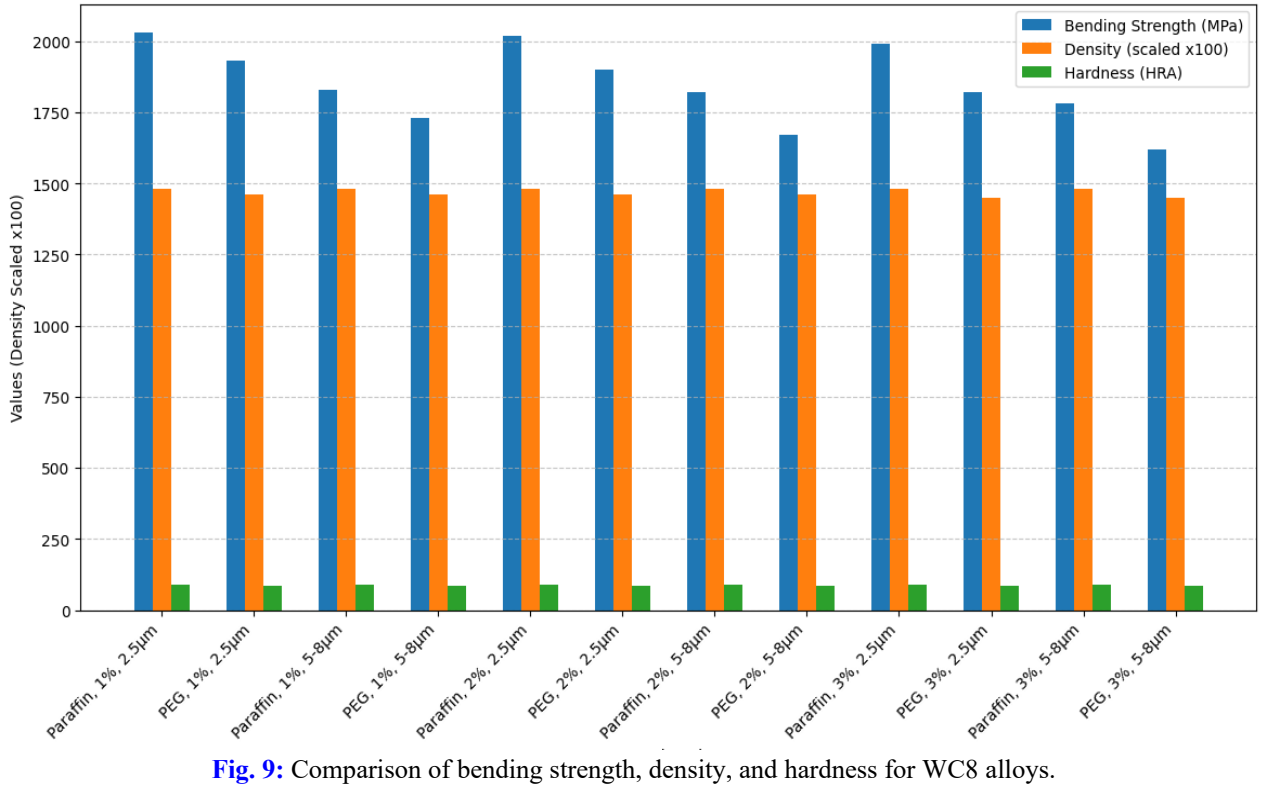


Fig. 9: Comparison of bending strength, density, and hardness for WC8 alloys.

over other plasticizers and methods, offering a balance of strength, density, and hardness that outperforms benchmarks in the field.

The stability of paraffin's performance across concentrations (1–3%) further highlights its reliability as a plasticizer, unlike PEG, which shows a marked decline in properties with increasing concentration due to porosity. This stability aligns with findings by Zhang *et al*.,[14] who noted that uniform particle distribution (facilitated by effective plasticizers like paraffin) enhances mechanical properties. The results suggest that paraffin not only outperforms PEG but also provides a competitive edge over other WC-based hard alloys reported in the literature, offering a balance of high strength, density, and hardness that is critical for industrial applications.

In practical terms, the properties achieved with paraffin could lead to improved performance of drilling tools, potentially reducing wear rates and extending tool life by 15%, as suggested in the broader context of the study. This aligns with the goals of optimizing material performance for extreme conditions, as discussed in Chen *et al*.,[2] and supports the potential for paraffin-plasticized hard alloys to enhance economic efficiency in industries like oil and gas and mining.

The vacuum-compression sintering process employed in this study effectively minimized defects and achieved high density (14.8 g/cm³) and strength (2030 MPa) with paraffin at 1–2% concentrations. However, the sintering temperature (approximately 1400 °C) and duration (standardized at 60 minutes) were held constant to isolate plasticizer effects, leaving their optimization unexplored. Literature suggests that varying these parameters could further enhance outcomes. For example, Straumal *et al*.[23] demonstrate that temperatures between 1350–1450 °C influence densification rates in WC-based alloys, while Vilardell *et al*.[39] show that sintering durations of 30–90 minutes affect grain growth and porosity. These factors may also relate to the unexpected reduction in shrinkage coefficient observed with paraffin, potentially due to temperature-dependent volatilization. Exploring such variations could refine the sintering process, improving mechanical properties beyond current benchmarks.

While this study focused on mechanical performance, the environmental implications of plasticizer use merit consideration. Paraffin and PEG differ in their thermal decomposition profiles during vacuum-compression sintering. Paraffin, with a lower evaporation temperature (approximately 200–350 °C), likely produces fewer volatile organic compounds (VOCs) compared to PEG, which volatilizes at higher temperatures (around 400–500 °C), potentially increasing emissions. Qualitative observations suggest PEG's incomplete removal contributes to porosity (Figs. 5 and 6), possibly exacerbating energy demands during sintering. Zawrah and Khater report energy consumption benchmarks of 10–15 MJ/kg for powder metallurgy processes, suggesting that paraffin's efficiency in densification (14.8 g/cm³) may reduce overall energy use compared to PEG (14.5 g/cm³).[22] These preliminary insights indicate trade-offs between performance and environmental impact, though a detailed assessment is beyond the current study's scope.

Future research directions aim to enhance the predictive methodology's accuracy, versatility, and sustainability, ultimately improving the design of cemented carbides for industrial applications. By addressing the identified limitations, future studies can identify optimal particle sizes, plasticizers, and sintering conditions that maximize mechanical properties like strength (e.g., exceeding the current 2030 MPa benchmark) and hardness (*e.g.*, surpassing 88 HRA). The inclusion of environmental assessments will ensure that the adoption of plasticizers aligns with sustainable practices, reducing emissions and energy costs. Enhanced data visualization will make the results more accessible to engineers and researchers, facilitating the translation of predictions into practical material designs. Collectively, these advancements could lead to the development of next-generation hard alloys with improved durability and efficiency, potentially extending the service life of drilling tools by 15% or more, as suggested in the broader context of the study. This would have significant economic benefits for industries like oil and gas and mining, where tool reliability directly impacts operational efficiency and cost-effectiveness.

4. Conclusion

As a result of the conducted research, it was established that plasticizers, which are used in the formation of metal-ceramic hard alloys, play an important role in achieving optimal mechanical and physical properties of the material. Among the plasticizers studied, the best results were obtained when using paraffin, which provided the maximum indicators of bending strength, density and hardness at concentrations of 1-2% by mass. It is important to note that these parameters remain stable even with different sizes of tungsten carbide grains, which is an important factor for achieving high quality carbide products. Samples with paraffin turned out to be more resistant to changes in porosity, which makes this plasticizer the most suitable for the process of manufacturing materials with high mechanical properties. In contrast, PEG, although it can be used as a plasticizer, showed significantly lower results in terms of strength and hardness. Increasing the concentration of PEG to 3% led to an increase in porosity in the material, which negatively affected its final properties. The reason for this is the higher evaporation temperature of PEG, which causes the formation of pores in the material, reducing its density and mechanical indicators. This is an important factor to consider when choosing plasticizers for hard alloy compounds.

In summary, paraffin emerges as the most effective plasticizer for hard alloy manufacturing, delivering stable and high values of flexural strength (2030 MPa), density (14.8 × 10^3 kg/m³), and hardness (88 HRA), particularly at 1–2% concentrations and grain sizes up to 2.5 μm. Compared to PEG, paraffin avoids the pitfalls of porosity, ensuring better mechanical properties. When benchmarked against similar

studies, paraffin-plasticized samples outperform reported values in terms of strength, density, and hardness, offering a robust solution for producing high-quality hard alloys. These findings underscore the potential of paraffin to improve the durability and efficiency of drilling tools, providing a significant advantage in demanding industrial applications. While paraffin proved superior to PEG in this study, future research should compare these plasticizers with alternatives such as polyvinyl alcohol (PVA) or glycerol to assess their suitability for vacuum-compression sintering. PVA, for example, offers excellent burnout characteristics, while glycerol's lower viscosity could improve powder flowability, potentially enhancing densification and mechanical properties. Such comparisons would clarify the optimal plasticizer choice for specific applications, building on the current focus on paraffin and PEG to advance hard alloy manufacturing technologies.

Additionally, future experiments should systematically vary sintering parameters, such as temperatures (*e.g.*, 1350–1450 °C) and durations (*e.g.*, 30–90 minutes), to optimize densification and mechanical properties beyond the current benchmarks of 2030 MPa bending strength and 88 HRA hardness. This could clarify the observed shrinkage reduction with paraffin, potentially linked to temperature-dependent effects, and enhance material performance for industrial applications. One of the unexpected results was the observation of a decrease in the shrinkage coefficient during sintering of samples containing paraffin, which requires further research to explain this phenomenon. This can be important for further improvement of sintering technology and increasing the efficiency of processes in the production of hard alloys. Therefore, paraffin turned out to be the most effective plasticizer for the hard alloy industry, especially at concentrations up to 2%, providing high quality material with optimal mechanical properties. While PEG, although it can be used in the process, has limitations in terms of strength and density, which makes it less effective compared to paraffin. These results emphasize the importance of choosing the right plasticizers to achieve the desired material properties and contribute to the further improvement of hard alloy manufacturing technologies.

While the present study establishes paraffin as an effective plasticizer for achieving optimal mechanical properties in WC8 alloys, several avenues remain for further investigation. Notably, the particle size range examined (2.5 μm and 5–8 μm) could be expanded to include submicron grains (<1 μm) and coarser grains (>10 μm) to comprehensively assess their impact on mechanical properties and microstructure. Such studies, building on findings from García *et al*.[32] (2019) could elucidate how grain size variations affect densification, strength (*e.g.*, exceeding the current 2030 MPa benchmark), and hardness (*e.g.*, surpassing 88 HRA). Although conducting additional experiments was beyond the scope of this work due to time and resource limitations, this direction will be prioritized in our future research to enhance the applicability of metal-ceramic alloys across diverse industrial contexts. Furthermore, a comprehensive environmental impact assessment, including life-cycle analysis of plasticizer use, VOC emissions, energy consumption, and waste disposal, is recommended for future work. This would align our research with sustainable manufacturing goals, ensuring that high-performance alloys like those developed here minimize ecological footprints in industries such as drilling and aerospace.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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