Scientific Research Publishing

Journal of Materials Science and Chemical Engineering, 2022, 10, 44-52
https://www.scirp.org/journal/msce
ISSN Online: 2327-6053
ISSN Print: 2327-6045

The Fabrication Method and Tribological Properties of Co-TiC Sintered High-Temperature Alloy

Oleksandr Tisov[1], Alina Yurchuk[2], Magda Wlazło-Ćwiklińska[3]

[1]School of Aerospace Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi, China
[2]Department of Computerized Electrotechnical Systems and Technologies, Aerospace Faculty, National Aviation University, Kyiv, Ukraine
[3]Department of Fundamentals of Technology, Faculty of Fundamentals of Technology, Lublin, Poland
Email: oleksandrtisov@xjtu.edu.cn, alina.yurchuk@npp.nau.edu.ua, m.wlazlo@pollub.pl

How to cite this paper: Tisov, O., Yurchuk, A. and Wlazło-Ćwiklińska, M. (2022) The Fabrication Method and Tribological Properties of Co-TiC Sintered High-Temperature Alloy. *Journal of Materials Science and Chemical Engineering*, **10**, 44-52.
https://doi.org/10.4236/msce.2022.104004

Received: April 12, 2022
Accepted: April 26, 2022
Published: April 29, 2022

Abstract

Turbine blades of aircraft gas-turbine engines were always the place to apply novel materials and technologies. Special attention was paid to strength, corrosion-oxidation, and tribological performance. The blade top-shrouds are one of the most vulnerable places from the point of wear resistance. This problem was usually solved by applying coatings (weld-deposition, electrospark coating, gas-spray coatings). The new method proposed here is to use soldering technology: the to-size plate manufactured of wear-resistant material is bonded to the friction surface by the solder with the composition close to the composition of the turbine blade. In this work, we propose the method and the material for improving the wear resistance of the turbine blade's top shrouds. The cobalt-based materials (Co-15Cr-2.5Fe-2.5Al-36TiC) seem very promising for this. In the present work, the manufacturing technology of the alloy by HIP method, microstructure, and high-temperature fretting-wear characteristics (1050˚C) are discussed.

Keywords

Heat Resistant Alloy, High-Temperature Fretting Wear, Hot Isostatic Pressing, Turbine Blades

1. Introduction

In increasing the reliability and service life of gas turbine engines (GTE), one of the most critical tasks is to ensure high wear-resistance of the contact surfaces of the top-shrouds of turbine blades [1] [2]. This issue became especially acute during the creation of a new generation of gas turbine engines, where, along with increasing the service life, the task was to increase by-to-fly ratio of the engine, which, accordingly, led to increased operating temperatures and loads. In [3] [4] they show that the soldering of the composite sintered Co-based alloys strengthened by TiC powders may be an effective method of increasing the wear resistance of top-shrouds. They may be manufactured by casting, but in this case, the volume fraction of carbides is 20 - 30 vol.%. Only sintering of pre-alloyed cobalt with titanium carbides may increase the volume fraction to the desired value. As estimated [3], the content of carbides should be about 36 wt%/50 vol.%. This work aims to study the manufacturing process parameters, microstructure, and wear resistance of HIP-sintered alloy composed of Co-15Cr-2.5Fe-2.5Al-36TiC (wt%).

2. Materials and the Methods

In the previous study [3], cast alloys were fabricated by electric arc melting. Melting was performed in an Argon atmosphere using a tungsten nonconsumable electrode. They did four remelting of castings, each time being turned over to achieve uniform distribution of elements in the alloy – this method allowed to increase the content of the carbide phase to 30% vol. Studies have shown that this alloy has a high heat resistance, which exceeds the heat resistance of the industrial blade alloy ZhS-32, and a reasonably high melting point and fine-grained carbide phase in the structure [5]. However, to increase the wear resistance, it is necessary to increase the content of the carbide phase further, but in hypereutectic alloys, there are coarse carbides and significantly increased alloy pouring temperature [6]. These circumstances reduce the ductility and wear resistance of the alloy and make it impossible to manufacture or deposit as a coating by electric arc melting. To increase the amount of dispersed crystals of the strengthening carbide phase in composite alloys.

Samples of powder alloys for the study were made using pre-alloyed cobalt powder and TiC powders (5… 10 μm). They were sintered by the VU-2M vacuum hot isostatic press. Sample porosity was determined by the hydrostatic method. The MFK-1 test machine, additionally equipped with a pipe-type electric furnace to simulate the conditions of high-temperature fretting, was used to assess the wear resistance of these alloys [5]. The use of a heating element made of Resistohm-145 alloy allowed to raise the maximum operating temperature to 1050˚C. The tests were performed in couples made of the same material under the following conditions: specific contact load - P = 30 MPa; the amplitude of the relative movement of the samples: A = 120 μm; oscillation frequency: 30 Hz; test duration: 5×10^6 cycles; ambient temperature: 650˚C - 1050˚C. As high temperature causes intensive scale formation and weight gain is more extensive than wear loss, we used the linear method (optimeter IKV-3) to determine the wear. To increase the accuracy, the surface of samples and counterparts was ground to Ra = 0.63 - 0.16 μm using automatic surface grinder model 3B722 with a constant supply of cooling liquid.

3. Results and Discussion

3.1. Manufacturing and Structure Analyses of Sintered Samples

The study of the sintering process, as well as the analysis of the structure of the obtained materials, allowed to identify the main factors influencing the structure [7] [8]:

- Sintering temperature;
- Soaking time;
- Sintering pressure.

The hot isostatic pressing method allows to obtain dense blanks and finished parts from heat-resistant alloys with high mechanical characteristics, and therefore it is essential to study the interaction of HIP parameters on the properties of compacted material. Insufficient compaction of the material can be the result of insufficient heating, as well as insufficient pressure and soaking time. The studies of the temperature effect revealed the best value between 1280˚C and 1320˚C, see **Figure 1**. The maximum density of the alloy is achieved at a temperature of hot isostatic pressing ~1300˚C, which is approximately 95% of the melting point of the doped cobalt matrix. With such heating, the matrix is quickly pressed and fills the space between the grains of the carbide phase. Increasing the temperature to 1330˚C - 1340˚C leads to increased porosity.

The application of small loads leads to mainly elastic deformations of the matrix. In such conditions, sintering is possible only through diffusion processes and creep. Using higher pressures will be more effective, immediately converting the matrix material into a plastic state. In combination with high temperatures, the absolute value of this pressure can be relatively small. As seen in **Figure 2**, the contact pressure is 5 MPa, which is enough to get a porosity of about 3% at 1300˚C.

Thus, at the optimum pressing temperature, which was determined earlier, increasing the pressure to 5 MPa allows to minimize porosity; the density of the pressed material is reached at the level of 95% - 98% of the theoretical one.

Applying high pressures can significantly reduce the time of hot pressing. However, titanium carbide powders contain free carbon. Therefore, its diffusion into the cobalt matrix is undesirable as it reduces the melting point. Thus, during the production of powder alloys, it was balanced by adding titanium hydride

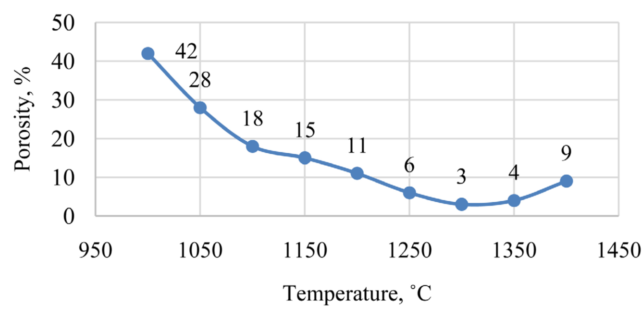


Figure 1. Dependence of porosity on sintering temperature at 5 MPa, soaking time 20 min.

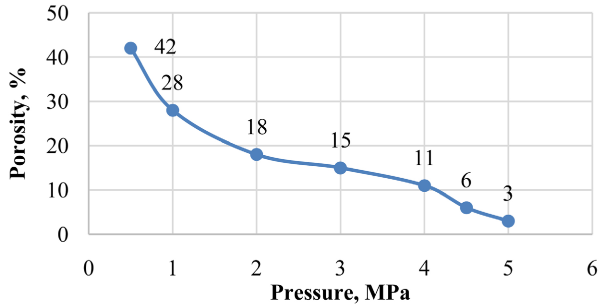


Figure 2. Dependence of porosity on sintering pressure at 1300˚C, soaking time 20 min.

in a stoichiometric ratio, which allowed (as a result of the addition reaction) to obtain more of TiC fine grains. However, it takes some time for the reaction to proceed completely, so rapid consolidation of powders using high pressures is not advisable. The research [9] [10] has shown that 8 - 10 minutes of holding at 1300˚C is sufficient for the binding of free carbon usually present in TiC [11], as well as for the partial dehydrogenation of the alloy, which continues during the soldering of the plates/samples to the base material.

Studies of the effect of soaking time on the porosity of the sintered material show that with insufficient duration of the process (less than 5 min), compacting of the material is not complete (see **Figure 3**). For full or maximum possible completion of these processes, keeping the original powders in a heated compressed state for about 15 minutes is sufficient. Further pressing under these conditions does not lead to a significant increase in density.

Thus, the HIP sintering of Co-15Cr-2.5Fe-2.5Al-36TiC alloy should be performed at the following parameters: temperature 1280˚C - 1320˚C; pressure 5 MPa; soaking time: 15 - 20 minutes. This will result in a non-porous microstructure or the microstructure with a minor amount of residual pores. The studies have shown that such alloys have the highest wear resistance in high-temperature fretting wear.

To assess the effect of the sample's microstructure (porosity) on their wear resistance, we tested the samples fabricated under different conditions. Their microstructure is in **Figure 4**.

As seen from **Figure 4(a)**, the size of pores is about 10 μm, with some of them acceding this value. They are primarily located in places with a higher concentration of coarse TiC particles (red arrows), while other sites are free of pores (green arrows). **Figure 4(b)** sample was sintered at lower pressure (4 MPa) but for a longer time (20 min), and the number of pores was much less, and their size was only about 1 μm (arrowed). Therefore, the P3 sample, **Figure 4(c)**, may be considered fully dense microstructurally. There were no voids between the matrix and TiC grains detected. According to the hydrostatic method, its density is 97% (3% porosity). As arrows indicate it, there are voids inside the grains of carbides, and we suppose that exactly they cause the indicated porosity of the alloy. TiC is approximately 1.78 times less dense than the cobalt matrix; thus, we may consider the actual alloy volume porosity is even less than 3%. So,

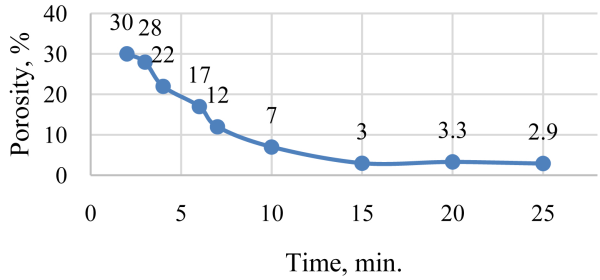
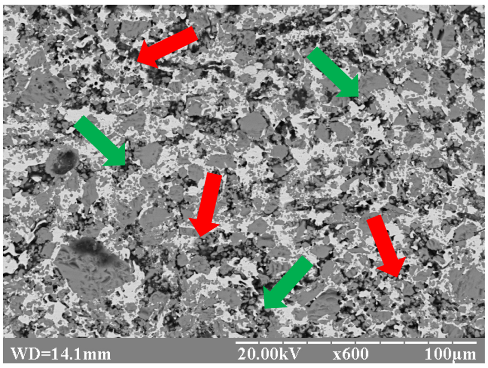
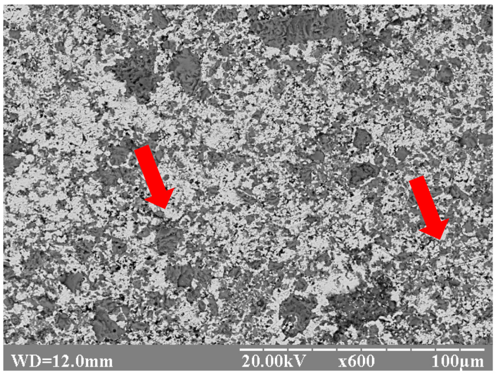


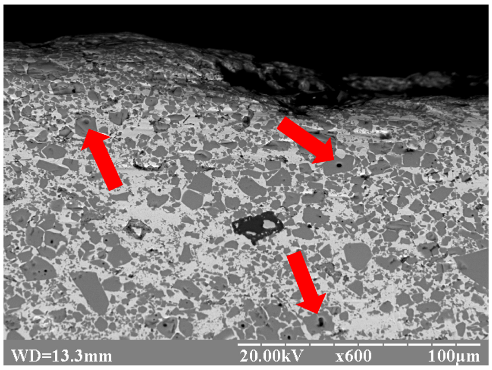
Figure 3. The effect of sintering time on the alloy porosity at the pressure of 5 MPa and sintering temperature of 1300˚C.



(a)



(b)



(c)

Figure 4. The microstructure of test samples with different porosity: (a) – 28% (1300˚C, 5 MPa, 3 min), (b) – 11% (1300˚C, 4 MPa, 20 min), (c) – 3% (1300˚C, 5 MPa, 15 min).

microstructure analyses prove that the selected above sintering conditions are enough to fabricate fully dense material.

3.2. Tribological Performance

The wear of composite sintered alloys at high-temperature fretting depends on the method of fabrication, structure, and properties of the strengthening phase, uniformity of its distribution, mechanical characteristics and structure, etc. For two sintered samples with identical chemical composition, there is a significant difference in the numbers and sizes of pores. The pores are mainly local clusters of titanium carbide grains, between which there is no matrix phase. They significantly affect the stress distribution in the material under the action of friction forces, namely—reducing the strength of the material. Thus, the porosity significantly impacts the friction and wear processes of composite alloys.

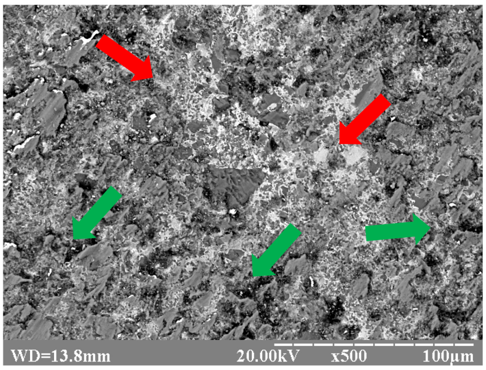
Wes did the tribological tests of 3 samples having an identical chemical composition containing 50/50 volume fractions (64Co/36TiC mass fractions) of alloyed cobalt and titanium carbide powder (powder size fraction is 5… 20 μm). The porosity of the samples was 3%, 11%, and 28%. The results of tribological studies are in **Table 1**.

The increase of material's porosity from 3% to 28% leads to 2.2 times increase in linear wear at 650˚C, 8.7 times at 900˚C, and 3.8 at 1100˚C. This can be explained by the fact that highly porous material cannot effectively redistribute the stresses arising from the action of friction forces inside the material and relax them. In the porous material, the layers of the cobalt matrix are subjected to elastic deformations under the act of external alternating load, the magnitude of which increases with increasing porosity. Such deformations are possible due to the presence of pores. This contributes to the accumulation of fatigue damage and the formation of microcracks, and not always on the carbide-matrix interface. Thus, the wear of the porous material is much higher than that of entirely dense.

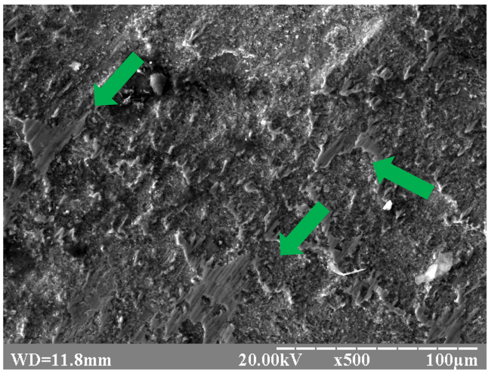
Porosity significantly affects the formation of protective oxide layers. There is the formation and accumulation of wear products in the friction zone during friction and other processes. However, the wear products first fill the pores (arrowed) on the friction surface in the porous material. Their size is big enough to accumulate a significant amount of wear products, thus avoiding the formation of a continuous oxide layer. As shown in **Figure 5(a)**, the surface is generally not

Table 1. The linear wear of the samples was tested at high-temperature fretting-wear.

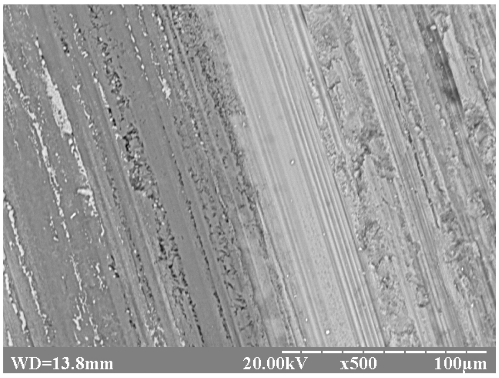
Alloy porosity, %	Alloy designation	Linear wear loss, μm		
		650˚C	900˚C	1100˚C
28	P28	33	253	380
11	P11	28	83	256
3	P3	15	29	103



(a)



(b)



(c)

Figure 5. The topography of alloys wear track indicating the increasing of friction-induced layer coverage as porosity decreases from 28% to 3% (alloys are the same as in **Figure 4**).

covered by the oxide layer. The alloy with 11% (**Figure 5(b)**) porosity has a much more developed oxide layer though it is not uniform and has quite a rough surface with areas elevated over the general surface. The dense alloy on **Figure 5(c)** friction surface is uniform, completely covered with oxide-type friction-induced layer. The lines along the friction path and some scars indicate the combination of abrasive, brittle fractures. Nevertheless, this alloy has the best tribological behavior. The wear of the alloy P11 with 11% of porosity is close to alloy P3. Increased wear loss indicates much higher wear intensity, though friction and wear mechanisms are similar. Also, we should mention a bigger size of wear products on **Figure 5(b)** than on **Figure 5(c)**. For **Figure 5(a)**, the wear mechanism is different. As it may be seen from the micrograph (red arrows), a significant surface area is not covered by oxides which causes adhesion wear combined with abrasion: uncovered carbide particles plough the conjugate surface. In addition, the falling off carbide particles augments abrasion. As we think, these 3 factors cause the significant wear of porous alloy (28% porosity).

The high wear resistance of surface structures formed during high-temperature fretting-wear is provided by structural stability and resistance to plastic deformations of the substrate material due to the optimal content of wear-resistant and heat-resistant filler (TiC particles, [11]). High contact loads are localized on the surface of friction-induced structures, and the stresses transmitted to the lower layers cause mainly elastic deformations, confirmed by metallographic analysis.

As for future studies, the wear resistance of Co-TiC sintered alloys may be improved in several ways, and they may be applied simultaneously. As we think, the use of spherical TiC particles will reduce the micro-cutting during friction and reduce the porosity by facilitating the matrix deformation during the HIP process. In addition, the absence of sharp edges inside the alloy reduces the internal stresses and crack initiation probability. However, it is also possible to increase the wetting of TiC by cobalt via the introduction of other alloying elements, like nickel, that do not cause a minimum reduction of melting point and heat resistance. Also, spherical or at least rounded carbides apply much higher sintering pressure with no risk of breaking them apart, thus initiating new crack sites.

4. Conclusion

Based on the analysis of tribological data of sintered alloys it was found that the alloy P3 with 3% hydrostatically measured porosity has minor metallographically determined pores and has the highest wear resistance. The wear mechanisms of alloys Co-15Cr-2.5Fe-2.5Al-36TiC, having different porosity have dissimilar wear mechanisms: oxidation-abrasive and brittle fracture (for alloys P3 and P11), while for alloy P28 it is adhesion-abrasive wear caused by fall-off of carbide particles and inability of forming continuous oxidation-type friction-induced layer. The high tribological characteristics of the P3 alloy were confirmed by tests in a wide range of temperatures. It has high wear resistance, which makes it promising as a material for application on the contact surfaces of top-shrouds of GTE turbine blades. For HIP sintering of these alloys the recommended pressure is 5 MPa at the temperature 1280˚C - 1320˚C during 15 minutes.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Tretiachenko, G.N., Kravchuk, G.N., Kuriat, R.I. and Voloshchenko, A.P. (1975) Bearing Capacity of Gas Turbines Blades at Nonstationary Haet and Force Effect, Kyiv.: Naukova Dumka [In Russian].

[2] Lieontiev, V.A., Zilichihis, S.D., Kondratiuk, Ye.V. and Zamkovoi, V.Ye. (2006) Recovery of Workability of GTE Using New Technologies and Materials. *Herald of Engine Constructing*, **4**, 99-103. [In Russian]

[3] Dmytrieva, H.P., Cherepova, T.S., Dukhota, O.I. and Nychyporenko, V.I. (2017) Investigation of Properties of Sintered Alloys Based on ZhS32-VI with Titanium Carbide. *Powder Metallurgy*, **11/12**, 68-75. [In Ukrainian]

[4] Cherepova, T.S., Dmitrieva, G.P., Nosenko, A.V. and Semirga A.M. (2014) Wear-Resistant Alloy for Protection of Contact Surfaces of Working Aircraft Engine Blades from Oxidation at High Temperatures. *Science and Innovation*, **10**, 20-28. https://doi.org/10.15407/scine10.04.020

[5] Cherepova, T., Dmitrieva, G., Tisov, O., Dukhota, O. and Kindrachuk, M. (2019) Research on the Properties of Co-Tic and Ni-Tic Hip-Sintered Alloys. *Acta Mechanica et Automatica*, **13**, 57-67. https://doi.org/10.2478/ama-2019-0009

[6] Holubets, V.M., Pashechko, M.I., Dzedzic, K., Borc J. and Tisov A.V. (2020) Frictional Strength of Electric Spark Coatings from Powder Wires under Friction without Lubrication. *Journal of Friction and Wear*, **41**, 443-446. https://doi.org/10.3103/s1068366620050128

[7] Razumovskiy, V.I., Lozovoi, A.Y. and Razumovskii, I.M. (2015) First-Principles-Aided Design of a New Ni-Base Superalloy: Influence of Transition Metal Alloying Elements on Grain Boundary and Bulk Cohesion. *Acta Materialia*, **82**, 369-377. http://dx.doi.org/10.1016/j.actamat.2014.08.047

[8] Jung, S.-A., Kwon, H., Suh, C.-Y., Oh, J.-M. and Kim, W. (2015) Preparation of a Fine-Structured TiC-Co Composite by High-Energy Milling and Subsequent Heat Treatment of a Ti-Co Alloy. *Ceramics International*, **41**, 14326-14331.

[9] Cherepova, T.S. and Dmytrieva, H.P. (2016) Properties of Titanium Carbide- Strengthened Cobalt-Based Sintered Alloys. *Metal Physics and Advanced Technologies*, **38**, 1497-1512. [In Ukrainian] https://doi.org/10.15407/mfint.38.11.1497

[10] Cherepova, T.S., Dmytrieva, H.P., Dukhota, O.I. and Kindrachuk, M.V. (2016) Properties of Nickel Powder Alloys Hardened with Titanium Carbide. *Mterials Science*, **52**, 173-179. https://doi.org/10.1007/s11003-016-9940-2

[11] Voytovich, R.F. (1981) Oxidation of Carbides and Nitrides, Kyiv, Naukova Dumka. [In Russian]