Tribological characteristics and structure formation of P6M5K5-TiC carbide steels for use in hybrid junctions of the metal-matrix composite-ceramic system

Stepan Kyryliuk, Genadii Bagliuk, Ostap Zgalat-Lozynskyy, Kostyantyn Grinkevych, Yevheniia Kyryliuk, Iaroslav Sytnyk
Frantsevich Institute for Problems in Materials Science, NASU, Kyiv, Ukraine, 03142, Krzhizhanovsky str., 3

Abstract: *The article investigates the influence of the technological parameters of manufacturing and the effect of the initial charge on the structure and tribological properties of carbide steel when used in hybrid components of the metal-matrix composite-ceramic system. It was found that the titanium carbide content of the initial charge was the determining factor in the formation of the properties. At the same time, an increase in the titanium carbide content above 20 (wt. %) does not lead to a significant increase in the hardness of the composite, and in some cases even to a decrease in hardness. It is also worth noting that the use of sprayed high-speed steel powder to prepare the mixture allows the composite to be obtained with fewer technological transitions. According to the results of tribological studies, it was found that the lowest wear was observed when the ceramics were paired with a composite with a titanium carbide content of 10 and 30 (wt. %). At the same time, the results of the analysis of friction track profilometry and the size of the contact patch showed that as the content of the carbide component increases to 30 (wt. %), a change in the nature of the friction occurs, accompanied by intensive wear of the ceramic ball. In the ceramic-carbide-steel (10 wt. % TiC) friction pair, however, no wear of the ceramic ball was observed, and the cross-sectional shape of the friction track changed from spherical to flat.*

KEYWORDS: *COMPOSITE MATERIALS, CARBIDE STEEL, RAPID STEEL, TRIBOTECHNICAL PROPERTIES, CERAMICS.*

Every year, the development of aircraft leads to the need to develop new materials that can operate under high loads, high temperatures and intense wear. This problem is caused by the need to ensure operating parameters in conditions of dry friction, high temperatures and variable loads due to failures in the cooling and lubrication system, one of the main representatives of such mechanisms being the rolling bearings used in aircraft. Such harsh operating conditions lead to rapid failure of bearing assemblies, resulting in loss of control of the aircraft. In view of this problem, manufacturers around the world have already switched to ceramic and hybrid bearings, with the most common being silicon nitride components. The defining parameters in the selection of this material were its high physical and mechanical properties, as well as its ability to withstand high temperatures at high speeds. These characteristics made it the best material for the base of the hybrid bearing balls. It is silicon nitride that can properly replace the outdated materials used in rolling bearings for operation in extreme conditions [1-8]. Due to their excellent impact resistance, exceptional strength and resistance to chemical and thermal factors compared to other ceramics, silicon nitride-based materials are considered very promising for the manufacture of all-ceramic or hybrid rolling bearings with extended service life.

When manufacturing a hybrid bearing, replacing only steel balls with ceramic balls can have the opposite effect. When operating a ceramic (ball) - steel (cage) friction pair, there is a high probability of rapid wear of the steel cage due to its low heat resistance, resulting in a loss of the required tribotechnical characteristics of the hybrid bearing and a rapid loss of performance. The problem of selecting the material and its manufacturing technology for use in conjunction with silicon nitride ceramic balls is also relevant. At the same time, it is necessary to ensure high tribotechnical characteristics that will allow the hybrid bearing to operate for a long time in extreme conditions [2]. In this case, the carbide steel of the P6M5K5-TiC system is the most promising for use in conjunction with silicon nitride-based ceramic balls. The HSS base provides high heat resistance, and titanium carbide inclusions will significantly increase the tribological properties of the composite. Another important factor is that the introduction of titanium carbide will reduce the weight of the bearing and, consequently, the entire unit as a whole.

The results of studies on the effect of titanium carbide content and carbide steel production technology on the structure and tribological properties when working with silicon nitride-based ceramics are of theoretical and practical interest.

Objects and research methods

The carbide steel of the P6M5K5-TiC system was produced by powder metallurgy, and compacted by hot stamping of spices. The initial charge was obtained by mixing the initial components in a gravity mixer of the 'drunken barrel' type. The mixture was prepared using sprayed P6M5K5 powder with a fraction of up to 100 microns, as well as industrial titanium carbide powder with an average particle size of 10 microns. The content of titanium carbide in the composite was 10, 20 and 30 (wt. %). The prepared mixture was pressed on a hydraulic press, with a specific pressing pressure of 800 MPa. Some of the pressings were sintered in a vacuum at a temperature of 1200 °C, with a sintering time of 1 hour. Further compaction was carried out by hot stamping in a semi-closed die, the heating temperature for hot forming was 1220 °C. After hot forming, the composite underwent heat treatment: hardening followed by tempering.

Ceramic balls of the Si_3N_4-ZrN_3 composition were obtained by consolidation by the SPS method in an HPD25 sintering furnace (FCT Systeme GmbH, Germany) of the initial mixture with an average particle size of 0.8 μm and 1.2 μm. Consolidation was carried out in a graphite die with graphite punches with a diameter of 20 mm and a cavity corresponding to the shape of a ball. The weight of the powder loaded into the matrix was 8.5 g. To prevent adhesion of the composite material to the punch, a boron nitride coating was applied to their inner surfaces. The study of tribological properties of these samples under dynamic indenter loading was carried out according to the method described in [9, 10] using the plane-ball scheme (dry friction). A ball of Si_3N_4 D=14 mm (unpolished) was used as a counterbody (indenter), and the test time was 900 seconds. The sliding speed was 0.0147 m/s. The temperature was T = 13 °C. The friction force, wear, and contact patch were determined during the tests.

The microstructure was analysed using a VEGA3 TESCAN electron microscope, and the Rockwell hardness was determined using a NOVOTEST TS-BRV stationary hardness tester.

Results and discussion

The comparative analysis of the hot-stamped carbide steel of the P6M5K5-TiC system obtained by different technological schemes has shown that in all cases the titanium carbide is located along the boundaries of the particles of the high-speed steel in the composite. The hardness of the composite (Table 1) shows that the hardness of the pre-sintered samples is almost the same as that of the samples without pre-sintering, and therefore we can conclude that the use of HSS powder makes it possible to obtain a composite with high hardness without additional technological operations.

Table 1 *– Composite hardness depending on the technological scheme of production*

TiC content, wt. %	Final hardness of the composite HRC			
	Non-sintered composite		Sintered composite	
	Heat treatment			
	Hardening + tempering	Tempering	Hardening + tempering	Tempering
10	68.0	57.5	62.0	56.0
20	64.0	62.5	67.5	65.5
30	62.0	63.0	68.5	61.0

A more detailed analysis of the hardness data shows that in all technological schemes, an increase in the content of titanium carbide from 10 to 20 (wt. %) leads to an increase in the hardness of the composite, while a further increase in the content of TiC to 30 (wt. %) does not lead to an increase in hardness and in some cases a decrease in the final hardness of the composite is observed. This effect can be explained by the fact that an increase in the content of titanium carbide from 20 to 30 (wt. %) leads to a significant decrease in the plastic flow of the composite, which leads to a deterioration in the density of the material, and therefore, after hot forming in the material with 30 (wt. %) TiC, the residual porosity is higher, which leads to a decrease in the hardness of the composite.

Fig. 1 shows the microstructure of the hot-stamped P6M5K5-30% TiC composite after tribological testing. As can be seen from

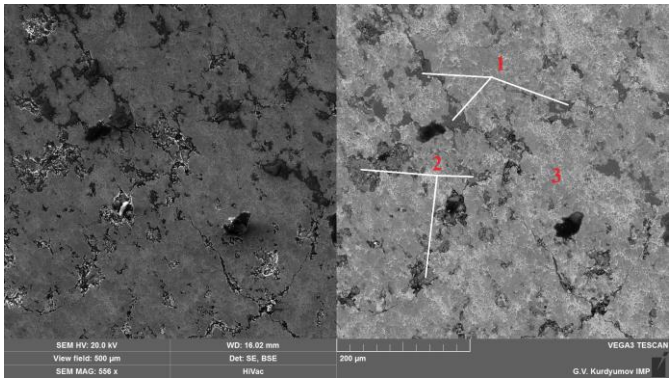

Fig. 1 *– Microstructure of hot-stamped P6M5K5-30% TiC composite*
1–Si_3N_4–ZrN_3; 2–TiC; 3–P6M5K5

the microstructure, the composite consists of a matrix 3 in which titanium carbide inclusions 2 are uniformly distributed. The microstructure image also shows residual porosity. A further examination of the microstructure shows that during the operation of the material in conjunction with the ceramic ball, wear products accumulate on the working surface and fill the existing cavities in material 1. At the same time, the results of local X-ray phase analysis showed that there is no diffusion of the ball material into the carbide steel material, and therefore the materials do not interact with each other when working in a pair.

Fig. 2 shows the tribological test data for a pair of Si_3N_4-ZrN_3 ceramics and P6M5K5-TiC carbide steel produced according to the technological scheme with pre-sintering and hardening. As can be

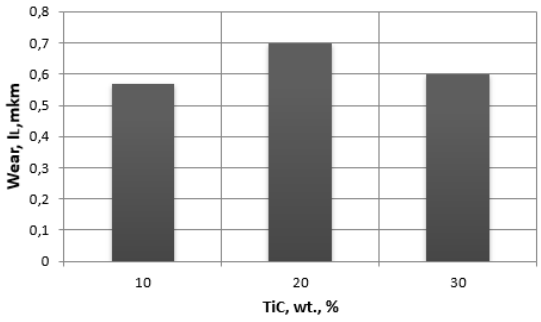

Fig. 2 *– Wear of the tribological pair of Si_3N_4-ZrN_3 ceramics and carbide-steel of the P6M5K5-TiC system*

seen from the graph, for this technological scheme of manufacturing, the linear wear, depending on the titanium carbide content, almost does not change. At the same time, the closest results were shown by the composites with a titanium carbide content of 10 and 30 (wt. %), with linear wear of the friction pair being 0.57 and 0.6 µm, respectively.

The analysis of the contact patch size after tribological tests for the same friction pairs (Fig. 3) showed that an increase in the titanium carbide content in carbide steel leads to an increase in the contact patch. This indicates that when the titanium carbide content increases from 20 to 30 (wt. %), the ceramic ball starts to wear out rapidly. Due to the large amount of carbide component in the carbide steel, a clearly defined mechanism of abrasive wear of the ball material is observed.

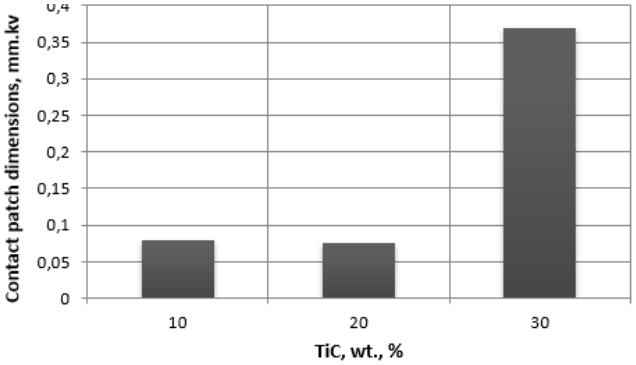

Fig. 3 *– Contact patch dimensions*

In turn, tribological tests carried out on samples obtained without preliminary sintering showed that the effect of the titanium carbide content in the composite is similar to that of the composites obtained with sintering.

Fig. 4 shows the profilograms of the friction tracks. The profilograms also show that when ceramics are paired with carbide steel with a titanium carbide content of 10 (wt. %), mainly carbide steel wears out and the shape of the friction track becomes spherical. When the titanium carbide content increases to 20 and 30 (wt. %), the material of the ceramic ball starts to wear. The shape of the friction track profile changes from convex to flat.

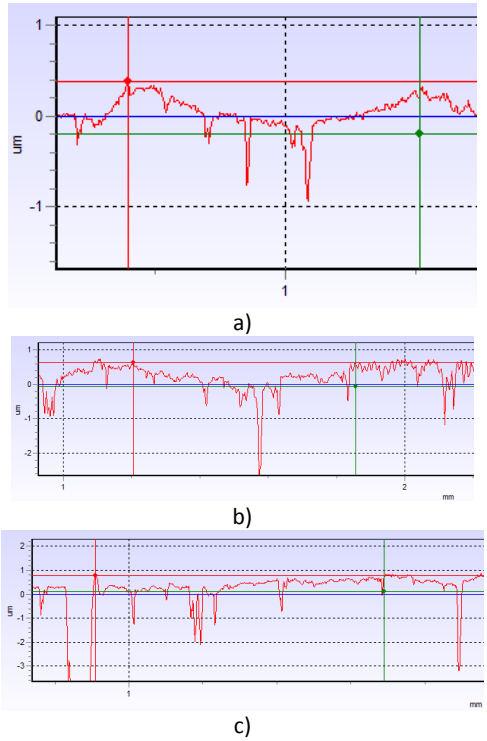

Fig. 4 *– Friction tracks profilograms*
a) 10% TiC; b) 20% TiC; c) 30% TiC

In view of the foregoing, we can conclude that the most promising in terms of ensuring the technological parameters and overall durability of hybrid metal-ceramic rolling elements is the ceramic (Si_3N_4-ZrN_3) – carbide steel (P6M5K5-10% TiC) pair. It provides high wear resistance and also ensures zero wear of the ceramic ball.

Conclusions

1. The influence of technological parameters of obtaining carbide steel of the P6M5K5-TiC system on its structure and properties has been studied. It has been shown that the use of HSS and titanium carbide powders for the preparation of the initial charge allows obtaining a carbide steel with titanium carbide uniformly distributed in the volume. It should also be noted that the use of mechanical mixing in the preparation of the initial charge ensures that the titanium carbide is distributed along the boundaries between the particles of the high speed steel. It is worth noting that the use of sprayed P6M5K5 powder makes it possible to obtain a composite of similar hardness without the need for an additional technological operation in the form of intermediate sintering. It has beem found that an increase in the titanium carbide content from 20 to 30 (wt. %) does not lead to a significant increase in the hardness of carbide steel, and in some cases leads to its decrease.

2. The results of the microstructural analysis have shown that during the friction process, wear products of the pore cavity are present on the surface of the material. The local X-ray phase analysis has also shown that there was no interaction between the ball and the carbide steel material during operation of the friction pair.

3. The results of tribological studies have shown that intermediate sintering does not have a significant effect on the wear resistance of the friction pair. The main influence on the friction pair durability is the titanium carbide content. The lowest wear is observed when ceramics are paired with a composite with a titanium carbide content of 10 and 30 (wt. %). Further studies have shown that the titanium carbide content of more than 20 (wt. %) changes the wear pattern and the material of the ceramic ball starts to wear intensively. This effect is also confirmed by the results of the friction track profilometry analysis.

References

1. Pallini, R.A.: “Turbine engine bearings for ultra-high temperatures”, SKF Ball Bearing Journal 234, September 1989.

2. Доценко В.Н./ В.Н. Доценко, С.В. Никитин // Авиационно- космическая техника и технология, 2008. – No8. – С. 138 – 144.

3. T. Fukudome, S. Tsuruzono, W. Karasawa, Y. Ichikawa 2002, “Development and Evaluation of Ceramic Components for Gas Turbine” ASME Paper GT-2002-30627.

4. Y. Etori, T. Hisamatsu, I. Yuri, Y. Yasutomi, T. Machida and K. Wada 1997, “Oxidation Behavior of Ceramics for Gas Turbine Combustion Gas Flow at 1500 ^{o}C” ASME Paper 97-GT-355.

5. K. L. More, P. F. Tortorelli, M. K. Ferber, L. R. Walker, J. R. Keiser, N. Miriyala, W. D. Brenrnall and J. R. Price 1999, “Exposure of Ceramics and Ceramic Matrix Composites in Simulated and Actual Combustor Environments” ASME Paper 99-GT-292.

6. B. Schenk, T. Stangman, E. J. Opila, R.C.Robinson, D. S. Fox, H. Klemm, C. Taut, K. More and P. Torterelli 2001, “Oxidation Behavior of Prospective Silicon Nitride Materials for Advanced Micro Turbine Applications” ASME Paper 2001-GT-0459

7. Boxman R. L., Zhitomirsky V. N., Grimberg I. et al. Structure and hardness of vacuum arc deposited multi-component nitride coatings of Ti, Zr and Nb // Surf. Coat. Technol. – 2000. – 125. – P. 257–262.

8. Wen M., Meng Q. N., Hu C. Q. et al. Structure and mechanical properties of δ-NbN/SiNx and δ′-NbN/SiNx nano-multilayer films deposited by reactive magnetron sputtering // Surf. Coat. Technol. – 2009. – 203. – P. 1702–1708.

9. Grinkevich, K.E. Some postulates of the structural dynamic concept of the tribosystem and its practical implementation. (2003) *Trenie i Iznos*, 24 (3), pp. 344-350.

10. Cyclic Indentation Method Applied to Evaluating Surface Degradation of Cylinder-Piston Group Parts. (2021) *Strength of Materials*, 53 (5), pp. 775-783.