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The Role of Diamond on Wear Properties of WC-Co Composite

Parinaz Pirmohammadi [a], Mohammad Zakeri [b,*], Monsour Razavi [b], Leila Nikzad [b]

[a] PhD Candidate, Department of Ceramics, Materials and Energy Research Center, Karaj, Iran
[b] Associate Professor, Department of Ceramics, Materials and Energy Research Center, Karaj, Iran
* Corresponding Author Email: m_zakeri@merc.ac.ir (M.Zakeri) URL: http://www.acerp.ir/article_90833.html

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ABSTRACT

There is a growing interest in researching materials to produce wear-resistant composites. This current study investigates the influence of adding 2.5 vol% diamond on the wear behavior of the WC-6% wt Co composite. The samples were fabricated using the spark plasma sintering method at 1300 °C for 5 minutes under 40 MPa. The pin-on-disk method was employed to study the wear behavior, followed by evaluating the worn surfaces using SEM analysis. According to the analysis of the worn surfaces, the addition of diamond to the WC-Co composite reduced the wear rate from 0.34×10^{-4} mm³/N·m to 0.25×10^{-4} mm³/N·m. Based on SEM images, abrasive wear was the main wear mechanism in the WC-Co composite, while abrasive, adhesive, and oxidation mechanisms were the primary wear mechanisms in the WC-Co sample reinforced with diamond phase. The presence of diamond as a hard phase within WC-Co composite significantly improved the wear resistance of the composite.

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1. INTRODUCTION

Modern industries are highly interested in materials that exhibit enhanced wear resistance. These materials provide significant benefits, including prolonged lifetime and the capability to withstand heavy tribological conditions [1-3]. WC-Co composites are extensively utilized in the aerospace industry and mechanical engineering due to their exceptional properties, such as high hardness and fracture toughness, which results in excellent wear resistance. For achieving optimal sintering results in WC-Co composites, the preferred method is SPS. This technique utilizes high-pulsed electric current and Joule heat to sinter the powder compact, ensuring efficient and effective consolidation [4]

Extensive research has been carried out with the aim of enhancing the wear characteristics and studying the wear mechanisms of WC-Co composites [5-8]. Research indicates that the wear characteristics of WC-Co can be enhanced by incorporating carbides like Ta, Nb, Cb, Ti, Mo, V and Cd into the hardmetals [9-11].

Pirso et al. conducted a study on sliding wear and friction behavior of WC–Co, Cr_3C_2–Ni, and TiC–NiMo composites. The results of block on ring test showed that the wear behavior of the Cr_3C_2–Ni cermet was influenced by their composition, whereas the wear response of the WC-Co and TiC-NiMo cermet was determined by the amount of binder present [11].

Bonny et al. investigated WC–Co–Cr_3C_2–VC composites and the results showed that addition of Cr_3C_2–VC to WC-Co, decreases the friction of the composite [12]. Quercia et al. studied the wear properties of WC–Co–(Ta,V)C composites under sliding, abrasion, and erosion conditions, and the results showed that mechanical properties and tribosystem configuration were the main effective factors on wear behavior of these composites. Addition of TiC to cemented carbides, increases abrasion resistant of WC-Co composite due to the more hardness of TiC compared to WC [13-14].

R. van der Merwe et al. studied how TaC, TiC, and NbC affect friction and dry sliding wear in WC–6 wt.% Co composite when interacting with steel surfaces. They found incorporating less than 1 wt.% TaC resulted in enhanced wear resistance. The primary wear mechanisms observed for the carbides were preferential removal of the binding material, grain cracking and fragmentation, carbide grain pull-out, and the formation of a protective film on the contact surfaces [15].

One way to enhance the wear resistance of WC-Co composites is by incorporating super-hard and wear-resistant materials such as diamond and cubic-BN [16-17]. The addition of diamond particles to WC-Co composites is expected to improve their wear behavior. This enhancement can be attributed to the extremely low friction coefficients, approximately 0.1, observed in diamond and chemical vapor deposition diamond coatings under dry running conditions [18-20].

Belji Yaman et al. demonstrated that the wear properties of tungsten carbide can be improved through the addition of cBN and the utilization of the SPS method [17]. Salvatore Grasso et al. conducted the ultrafast SPS process to fabricate diamond binder less WC composites. The presence of diamond as an additive resulted in a reduction in the wear rate and a decrease in the friction coefficient of these composites from 0.328 to 0.117 [9].

The fabrication of diamond hard-metal composites at low pressure poses significant technological challenges due to the thermodynamic instability of diamond under these conditions, leading to the graphitization of diamond [21].

The cemented carbide composite is known for its remarkable wear properties. In previous studies, high percentages of diamond with larger grain sizes were commonly used as reinforcement for these composites. However, it is anticipated that even low percentages of diamond can enhance the wear properties of cemented carbide, due to the remarkable properties of diamond. Therefore, it is essential to investigate the role of even a small amount of diamond in the wear mechanism of composites that use finer-grained diamond. In this research, we focused on investigating the effect of diamond presence on wear mechanisms, using the SPS method for consolidation. The worn surfaces were analyzed by scanning electron microscopy.

2. MATERIALS AND METHODS

The aim of the current study is to evaluate the effect of using diamond as an additive on the wear properties of the WC-Co composite. Therefore, two samples were prepared, one with 2.5Vol% diamond additive and another without the additive.

High-purity commercial powders WC (Almase Saz Co., 0.5µm, 99.9%), Co (Almase Saz Co.,1µm, 99.9%) and diamond (Henan Huanghe whirlwind Co., China, 10µm, 99 %) powder as reinforcement were mixed in a planetary mill with cemented carbide balls in an ethanol environment with a rotation speed of 120 rpm for 3 hours. After drying the mixture and passing it through a sieve with a 50 µm mesh, were poured into a graphite mold with an inner diameter of 30 mm. The sintering process carried out in an SPS-20T-10 machine made in China. The samples were spark plasma sintered in 1300 ˚C under 40 MPa for 5 min. Finally, the samples cooled to room temperature under a pressure of 40 MPa. After sintering, the samples were cleaned of graphite using a cubic-BN disk, polished with SiC papers and, finally mirrored with 2, 1, and 0.5 µm diamond paste.

In order to investigate the wear behavior of the samples, pin-on-disk wear test utilized. Figure 1 shows the schematic of the sample and the wear device for the wear test. The wear test was performed at room temperature in dry condition, using SiC abrasive pin with sliding speed of 0.07 m/s, under normal load of 38.2 N, and sliding distance was 800 m. The wear rate is defined as follows [22]:

$$\text{Wear rate} = \frac{V}{N.S} \qquad (1)$$

Where V, N and S are the volume loss of the specimen (mm^3), the normal load (N), and the sliding distance (m) respectively. The volume loss was obtained from the following equation [22]:

$$\text{Volume loss (V)} = \frac{(\pi R d^3)}{6r} \qquad (2)$$

Where R, d, and r are the wear track radius (mm), the wear track width (mm), the pin radius (mm) after wear tests respectively.

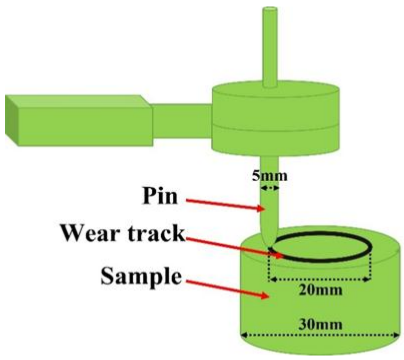

Figure 1. Schematic of the wear device and sample for the pin-on-disk test

The worn surfaces of samples were investigated by scanning electron microscope (FESEM; TESCAN MIRA3) and its elemental composition was analyzed by energy dispersive spectroscopy (EDX). The phase composition of the SPSed sample was determined with a Philips-PW3710 X-ray diffractometer with Cu Kα radiation (λ=0.15406 nm).

3. RESULTS AND DISCUSSION

In Figure 2, in order to understand the wear behavior of the prepared samples, the worn surfaces after 800m wear are shown in low magnifications SEM images.

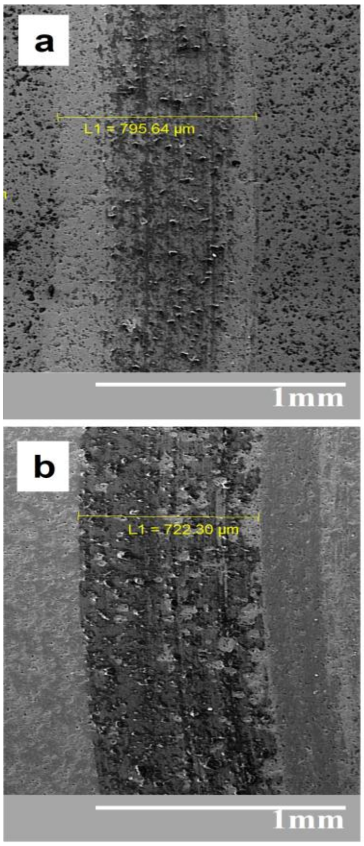

Figure 2. SEM images (Low magnification) of worn surfaces of a. D0, and b. D2.5

An inverse relationship exists between the width of the worn surface and the wear resistance of the sample. In the D2.5 sample, the width of the worn track has decreased, indicating an improvement in the wear resistance of the sample.

Fig. 3 shows the changes of width of worn surfaces and the wear rate (as two main parameters to evaluation of wear resistance) for samples with diamond reinforcement and free diamond sample.

With comparison of width of worn surface for the samples, it was found that sample free diamond has the lower wear resistance than sample containing diamond. It is seen that the width of worn surface and wear rate values for the sample free diamond is 795 µm and 0.34×10^{-4} $mm^3/N.m$, respectively.

After incorporating 2.5 Vol% diamond into the WC-Co matrix, significant improvements in wear resistance were observed. The width of the worn surface was reduced to 722 µm, and the wear rate decreased to 0.25×10^{-4} $mm^3/N.m$, indicating an enhancement in wear resistance compared to the previous condition.

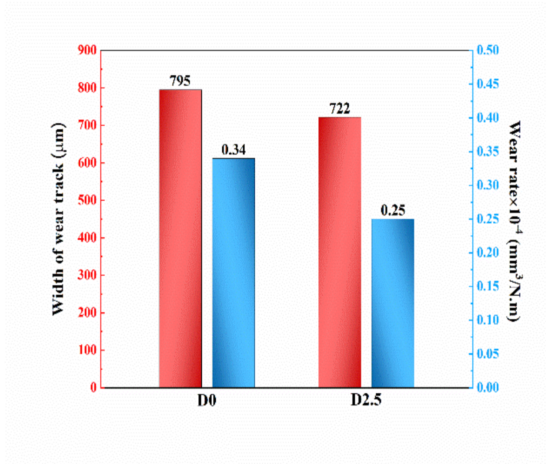

Figure 3. Variation of average width of worn surface, and wear rate for sample contained diamond and sample free diamond

According to the previous study [19], the hardness increases from 21.2 to 21.7 GPa by adding 2.5Vol% of diamond reinforcement to the matrix due to reinforcing effect of diamond particles. Increasing the hardness can positively affect the wear resistance of the samples. In order to investigate the underlying wear mechanisms, the worn surface of the samples has been studied with high-magnifications SEM images and EDS analysis in more detail.

In Fig. 4, SEM micrograph of the worn surface of D0 sample has been shown. It is seen, ploughing grooves mechanism in the sliding direction that represents abrasive wear throughout the worn surface due to continuously movement of high hardness pin on the surface of the sample, has occurred.

It appears that some of the soft cobalt phase was removed from the sample, and the tungsten carbide grains experienced wear. Furthermore, due to the continuous movement of the pin, a portion of the soft cobalt phase underwent plastic deformation and stretched across the sample's surface.

EDS analysis has revealed the presence of tungsten, carbon, and cobalt as constituents of the sample. Additionally, there is a very small amount of silicon, approximately 0.28 Wt%, which is related to the pin used for the wear test. This silicon was pull out from the pin and attached to the sample during the interaction. Moreover, there is a small amount of oxygen, approximately 0.62 Wt%, which is a result of partial oxidation during the wear test.

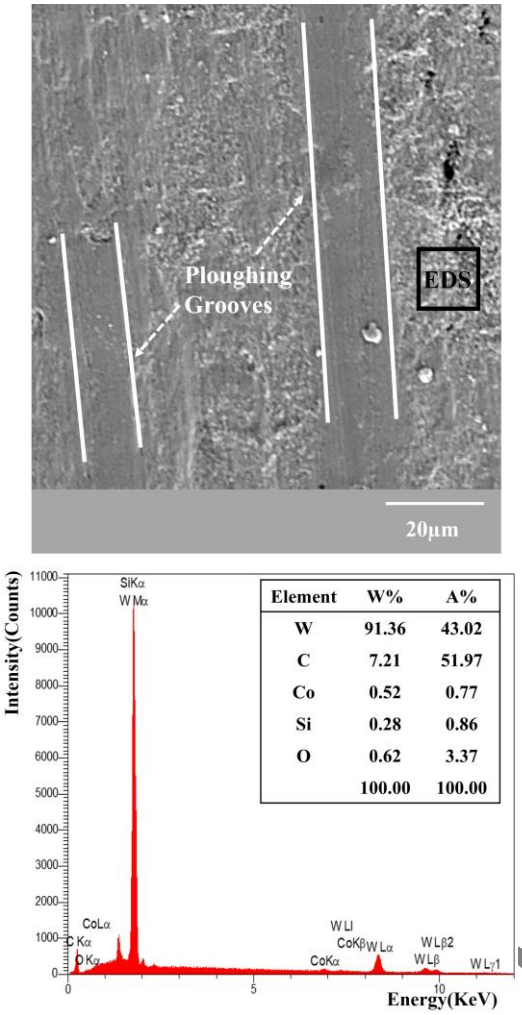

Figure 4. SEM micrograph and EDS analysis related to the worn surface of D0 sample

The XRD of the diamond-reinforced composite sample is presented in figure 5. The primary peaks observed in the sample are related to tungsten carbide. As is evident, in addition to the peaks corresponding to tungsten carbide, cobalt and diamond peaks are also evident. The comparatively lower intensity of the cobalt and diamond peaks is due to the high absorbtion of WC and the lower amount of diamond and cobalt compared to the WC phase.

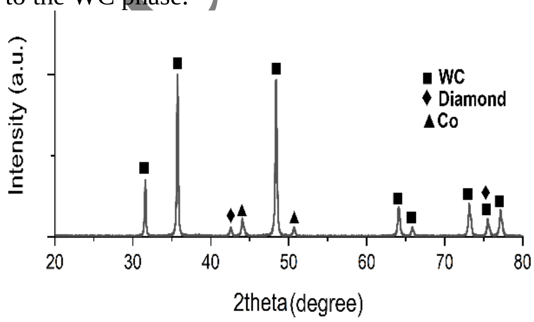

Figure 5. The XRD of D2.5 sample

As shown in Fig 6 of the SEM analysis of the fracture surface of the D2.5 sample, a dark phase is evenly distributed in the WC-Co matrix. According to the EDS analysis, this dark phase consists of diamond. The presence of tungsten and cobalt in the EDX spectrum is attributed to the presence of tungsten carbide and cobalt within the matrix.

Figure 7 depicts the SEM image displaying the worn surfaces of the D2.5 sample. Examination of these worn surfaces confirms the presence of pin elements through analysis using EDS. The presence of pin elements is a clear indication of the adhesive wear mechanism occurring in the D2.5 sample.

Additionally, the EDS results reveal the detection of oxygen on the worn surface of the composite samples, implying the involvement of an oxidation mechanism during the wear process.

Diamond exhibits higher thermal conductivity compared to tungsten carbide. This elevated thermal conductivity facilitates increased heat transfer to the sample during wear, unlike sample without additives. As a result, the temperature of the sample rises more significantly during wear, thereby enhancing the oxidation reaction compared to sample without additives. Therefore, the presence of diamond in the sample is more advantageous for oxide layer formation.

The presence of an oxide layer on the worn surface has a positive effect on wear resistance as it acts as a protective barrier. This oxide layer prevents direct contact between the pin and the sample, thereby reducing friction and wear between the two surfaces.

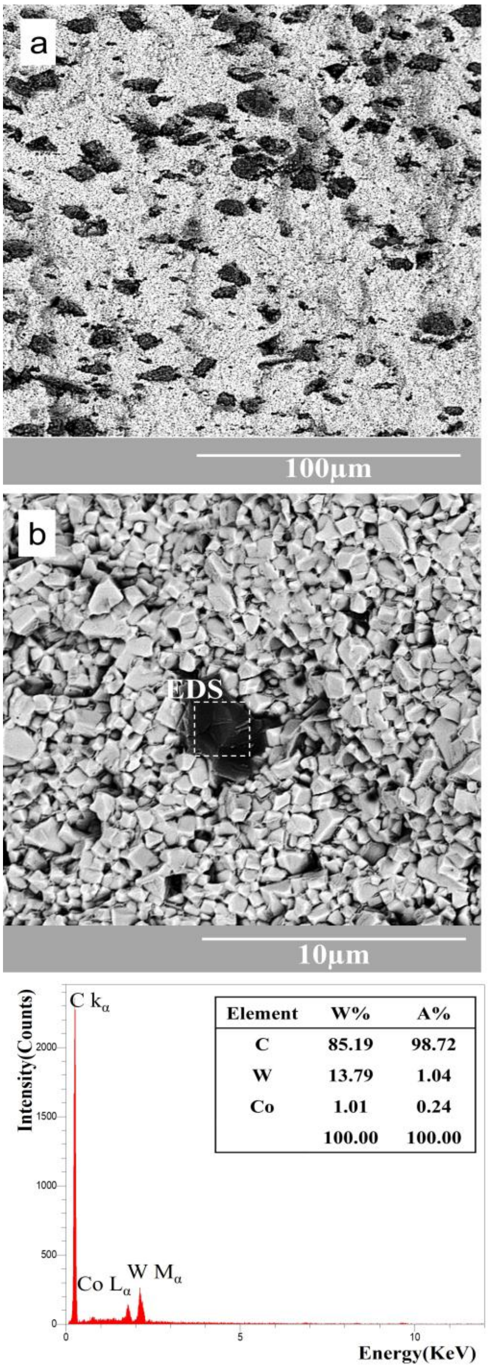

Figure 6. SEM image of fracture surface of D2.5 sample a. low magnification, and b. high magnification

The higher content of Si element observed in the worn surface of the D2.5 sample can be attributed to the increased interaction between the pin and the sample surface. This higher interaction likely leads to the pull out of Si from the pin and adhesive on the sample surface during the wear process. Thus, addition of diamond to WC-Co composites resulted in a changing the wear mechanism from abrasion mechanism to a combination of oxidation, adhesion, and abrasion mechanisms. This change in wear behavior can be attributed to the enhanced hardness of the composite samples achieved through the addition of diamond and uniform distribution of reinforcement. The increased hardness promotes greater interaction between the counter surface and the composite sample, leading to the observed alteration in the wear mechanisms

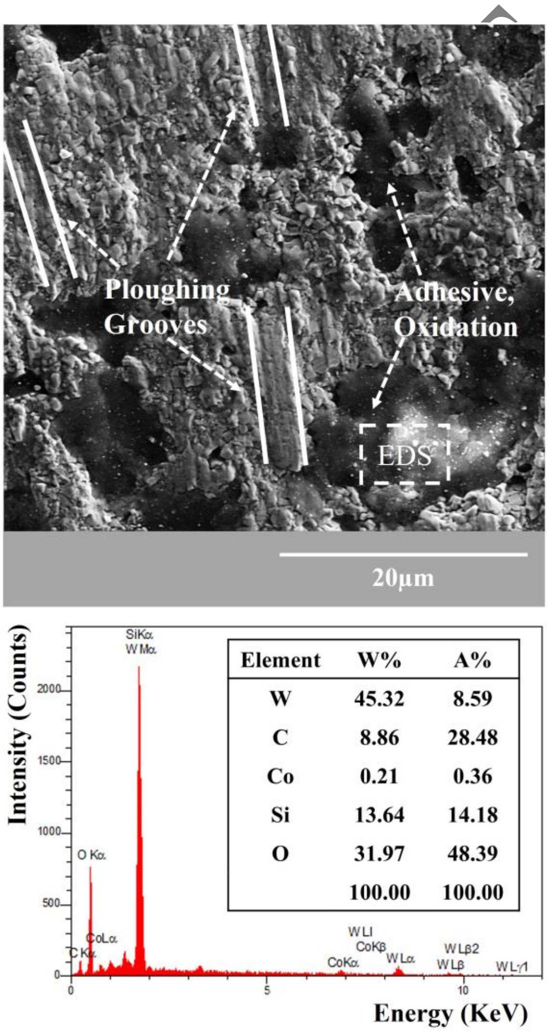

Figure 7. SEM micrograph related to the worn surfaces of D2.5 sample

As illustrated schematically in Figure 8-a, the main wear mechanisms observed in the D0 sample is abrasive mechanisms. These include the removal of a portion of the soft cobalt phase from the surface and ploughing of the tungsten carbide phases. Additionally, a partially adhesive mechanism is observed. As depicted schematically in Figure 8-b, the main wear mechanisms observed in this sample involve abrasive and adhesive mechanisms. These mechanisms encompass the removal of a portion of the soft cobalt phase from the surface and partial ploughing of the tungsten carbide phases.

Furthermore, an increased occurrence of adhesive mechanism is observed, particularly on the diamond phases present on the surface of the sample, compared to the free diamond sample.

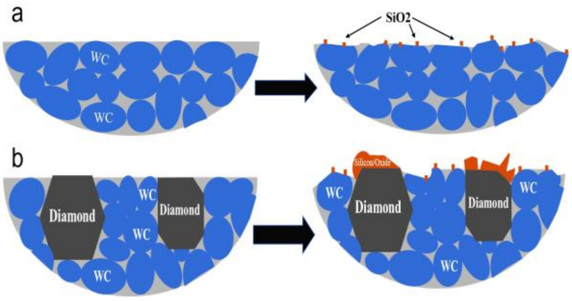

Figure 8. Schematic of wear mechanism in samples a. D0 and b. D2.5

4. CONCLUSION

In this study, the SPS method was utilized to fabricate WC-Co-2.5 vol.% Diamond and WC-Co samples, and the wear behavior of these samples was examined. The wear test results demonstrated a significant improvement in wear resistance for the WC-Co sample reinforced with diamond particles when compared to the pure WC-Co sample. The wear rate of the unreinforced WC-Co sample was 0.34×10^{-4} mm³/N·m, which decreased to 0.25×10^{-4} mm³/N·m after incorporating 2.5 vol.% diamond. In the pure WC-Co sample, abrasive wear was the predominant wear mechanism. However, the addition of diamond particles to the WC-Co matrix led to a complete change in the wear mechanism. The reinforced samples exhibited a combination of oxidation, adhesive, and abrasive mechanisms during the wear process. The results demonstrated that diamond can effectively be used as a reinforcement to enhance the wear resistance of WC-Co composites.

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REFERENCES

1. Holmberg, K, Ronkainen, H, Laukkanen, A, Wallin, K. "Friction and wear of coated surfaces scales, modelling and simulation of tribomechanisms", ***Surface and Coatings Technology***, vol. 202, (2007),1034–1049. https://doi.org/10.1016/j.surfcoat.2007.07.105

2. Van Acker, K, Vanhoyweghen, D, Persoons, R, Vangrunderbeek, J. "Influence of tungsten carbide particle size and distribution on the wear resistance of laser clad WC/Ni coatings", ***Wear***, Vol. 258, (2005), 194–202. https://doi.org/10.1016/j.wear.2004.09.041

3. Bonny, K, De Baets, P, Ost, W, Vleugels, J, Huang, S, Lauwers,B, et al. "Influence of electrical discharge machining on the reciprocating sliding wear response of WC–Co cemented carbides", ***Wear***, Vol. 27, (2009), 350–359.

   https://doi.org/10.1016/j.ijrmhm.2008.09.002

4. Ma, R, Ju, Sh, Chen, H, Shu, Ch, "Effect of Cobalt Content on Microstructures and Wear Resistance of Tungsten Carbide–Cobalt Cemented Carbides Fabricated by Spark Plasma Sintering", ***IOP Conference Series: Materials Science and Engineering***, Vol. 207 (2017). 012019. DOI10.1088/1757-899X/207/1/012019

5. Beste, U, Jacobson, S, "A new view of the deterioration and wear of WC/Co cemented carbide rock drill buttons", ***Wear***, Vol. 264, (2008), 1129–1141. https://doi.org/10.1016/j.wear.2007.01.030

6. Saito, H, Iwabuchi, A, Shimizu, T, "Effects of Co content and WC grain size on wear of WC cemented carbide", ***Wear***, Vol. 261, 2006, 126–132. https://doi.org/10.1016/j.wear.2005.09.034

7. JY, S.A, JA, B, "The wear characteristics of some cemented tungsten carbides in machining particleboard", ***Wear***, Vols. 225–229, (1999), 256–66.

   https://doi.org/10.1016/S0043-1648(98)00361-5

8. Gant, A.J, Gee, M.G, "Abrasion of tungsten carbide hard metals using hard counterfaces", ***International Journal of Refractory Metals and Hard Materials***, Vol. 24, (2006),189–198.

   https://doi.org/10.1016/j.ijrmhm.2005.05.007

9. Bonny, K, Baets, P.De, Perez, Y, Vleugels, J, Lauwers, B, "Friction and wear characteristics of WC–Co cemented carbides in dry reciprocating sliding contact", ***Wear***, Vol. 268, (2010), 1504–1517. https://doi.org/10.1016/j.wear.2010.02.029

10. Brookes, K, "Hardmetals and other hard materials", 3rd ed.Exeter: BPC Digital Information Limited, 1998.

11. Pirso, J, Viljus, M, Letunovitš, S, "Friction and dry sliding wear behaviour of cermets", ***Wear,*** Vol. 260, (2006), 815–824.

    https://doi.org/10.1016/j.wear.2005.04.006

12. Bonny, K, De Baets, P, Vleugels, J, Huang, S, Van der Biest, O, Lauwers, B. "Impact of Cr_3C_2/VC addition on the dry sliding friction and wear response of WC–Co cemented carbides", ***Wear***, Vol. 267, (2009),1642–1652.

    https://doi.org/10.1016/j.wear.2009.06.013

13. Quercia, G, Grgorescu, I, Contreras, H, Di Rauso, C, Gutierrez-Campos, D, "Friction and wear behaviour of several hard materials", ***International Journal of Refractory Metals and Hard Materials***, Vol.19, (2001), 359–369.

    https://doi.org/10.1016/S0263-4368(01)00028-2

14. Budinski, K.G, Budinski, M.K, "Engineering Materials, Properties and Selection", 7th ed. New Jersey: Prentice Hall; (2002).

15. van der Merwe, R, Sacks, N, "Effect of TaC and TiC on the friction and dry sliding wear of WC–6 wt.% Co cemented carbides against steel counterfaces", ***International Journal of Refractory Metals and Hard Materials,*** Vol.41, (2013) 94–102.

    https://doi.org/10.1016/j.ijrmhm.2013.02.009

16. Grasso, S, Hu, C, Maizza, G, Sakka, Y, “Spark plasma sintering of diamond binderless WC composites”, ***Journal of American Ceramic Society***, Vol. 95, No. 8, (2011), 2423–2428. https://doi.org/10.1111/j.1551-2916.2011.05009.x
17. Yaman, B, Mandal, H, “Wear performance of spark plasma sintered Co/WC and cBN/Co/WC composites”, ***International Journal of Refractory Metals and Hard Materials***, Vol. 42, (2014) 9-16. https://doi.org/10.1016/j.ijrmhm.2013.10.010
18. Habig, K.H, “Fundamentals of the tribological behaviour of diamond, diamond like carbon and cubic boron nitride coatings”, ***Surface and Coating Technology***, Vols.76–77, (1995) 540–547. https://doi.org/10.1016/0257-8972(95)02548-0
19. Hollman, P, Wänstrand, O, Hogmark, S, “Friction properties of smooth nanocrystalline diamond coatings”, ***Diamond and Related Materials***, Vol.7, (1998) 1471–1477. https://doi.org/10.1016/S0925-9635(98)00215-5
20. Hayward, I.P., “Friction and wear properties of diamonds and diamond coatings”, ***Surface and Coating Technology,*** Vol. 49, (1991), 554–559. https://doi.org/10.1016/0257-8972(91)90116-E
21. Ganta, A.J, Konyashin, I, Ries, B, McKie, A. Nilen, R.W.N. Pickles, J. “Wear mechanisms of diamond-containing hardmetals in comparison with diamond-based materials”, ***International Journal of Refractory Metals & Hard Materials***, Vol. 71, (2018), 106-114. https://doi.org/10.1016/j.ijrmhm.2017.10.013
22. ASTM-G99-05, ***Standard Test Method for Wear Testing with a Pin-On-Disk Apparatus***, Reapproved, (2010).
23. Pirmohammadi, P, Zakeri, M, Razavi, M, Nikzad, L, “Effect of diamond volume fraction on the microstructure and mechanical properties of SPS WC–Co/diamond composites”, **International Journal of Applied Ceramic Technology**, 2023.