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

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ABSTRACT

There is a growing interest in researching materials to produce wear-resistant composites. The current study aims to investigate the impact of adding 2.5 vol% diamond on the wear behavior of the WC-6% wt. Co composite. The samples were first fabricated using the spark plasma sintering method at 1300 °C for five minutes under the pressure of 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 results from the worn surfaces analysis, 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. According to the SEM images, abrasive wear was the main wear mechanism in the WC-Co composite while the 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 keenly interested in materials that exhibit enhanced wear resistance since these materials provide significant advantages including prolonged lifetime and ability to withstand heavy tribological conditions, to name a few (Holmberg, et al., (2007), Van Acker, et al., (2005), Bonny, et al.,(2009)). WC-Co composites are extensively used in the aerospace industry and mechanical engineering sectors due to their outstanding properties such as high hardness and fracture toughness, resulting in exceptional wear resistance. To achieve optimal sintering results in the WC-Co composites, SPS method is preferred. This technique employs high-pulsed electric current and Joule heat to sinter the powder compact, ensuring efficient and effective consolidation (Ma, et al., (2017)).

Extensive research has been carried out to enhance the wear characteristics and investigate the wear mechanisms of WC-Co composites (Beste & Jacobson, (2008))(Saito, et al.,(2006)) (JY & JA, (1999)) (Gant & Gee, (2006)). Studies indicate that the wear characteristics of WC-Co can be improved by incorporating carbides like Ta, Nb, Cb, Ti, Mo, V, and Cd into the hardmetals (Bonny et al., (2010)) (Brookes, (1998)) (Pirso, (2006)).

Pirso et al., (2006) 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

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showed that the wear behavior of the Cr_3C_2–Ni cermet was influenced by their composition while the wear response of the WC-Co and TiC-NiMo cermet was determined by the amount of binder present.

Bonny et al., (2009) investigated WC–Co–Cr_3C_2–VC composites, remarking that addition of Cr_3C_2–VC to WC-Co decreased the composite friction. Quercia et al., (2001) studied the wear properties of WC–Co–(Ta,V)C composites under sliding, abrasion, and erosion conditions, proving that the mechanical properties and tribosystem configuration were the key factors affecting the wear behavior of these composites. Moreover, addition of TiC to cemented carbides enhanced the abrasion resistant of WC-Co composite due to the higher hardness of TiC than that of WC (Quercia, et al., (2001)) (Budinski & Budinski, (2002)).

van der Merwe & Sacks (2013) studied how TaC, TiC, and NbC could affect friction and dry sliding wear in WC–6 wt.% Co composite when interacting with steel surfaces. They found that 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 formation of a protective film on the contact surfaces.

One way to enhance the wear resistance of the WC-Co composites is to incorporate super-hard and wear-resistant materials such as diamond and cubic-BN (Grasso, et al., (2011)) (Yaman & Mandal (2014)). Incorporation of the diamond particles into the WC-Co composites is expected to improve their wear behavior, and this improvement is attributed to the extremely low friction coefficients, approximately 0.1, observed in diamond and chemical vapor deposition diamond coatings under dry running conditions (Habig, (1995) (Hollman, et al., (1998)) (Hayward, (1991)).

Belji Yaman et al. demonstrated that the wear properties of tungsten carbide would be improved by adding cBN and using the SPS method (Yaman & Mandal, (2014). Salvatore Grasso et al., (2011) 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.

Fabrication of diamond hard-metal composites at low pressures poses significant technological challenges due to the thermodynamic instability of diamond under these conditions, leading to the graphitization of diamond (Ganta, et al., (2018)).

The cemented carbide composite are renowned for their 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 owing 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 contain finer-grained diamond. The present research primarily focused on the effect of diamond presence on wear mechanisms, using the SPS method for consolidation. The worn surfaces were analyzed through 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. To this end, two samples were prepared, one with 2.5 Vol% 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 the reinforcements were mixed in a planetary mill with cemented carbide balls in an ethanol environment at the rotation speed of 120 rpm for 3 hours. After drying the mixture and passing it through a sieve with a 50 µm mesh, it was poured into a graphite mold with the inner diameter of 30 mm. The sintering process was carried out in an SPS-20T-10 machine from 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.

To investigate the wear behavior of the samples, pin-on-disk wear test was done. Figure 1 shows the schematic of the sample and wear device used for the wear test. The wear test was conducted at room temperature in dry condition, using a SiC abrasive pin with the sliding speed of 0.07 m/s, normal load of 38.2 N, and sliding distance of 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), normal load (N), and sliding distance (m) respectively. The volume loss was obtained from the following equation (ASTM-G99-05(2010)):

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

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

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

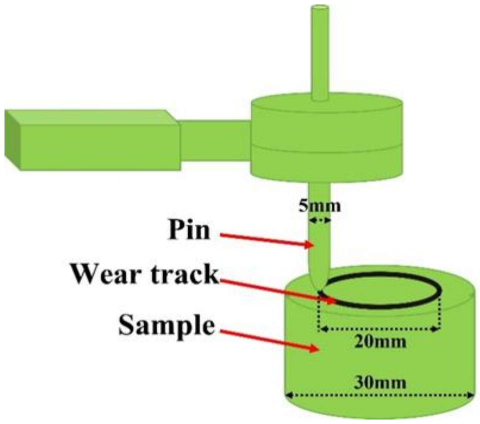


Figure 1. Schematic of the wear device and sample for the pin-on-disk test

3. RESULTS AND DISCUSSION

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

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

Figure 3 shows the changes of width of worn surfaces and wear rate (as two main parameters to evaluation of wear resistance) for samples with diamond reinforcement and without diamond.

Upon comparing the worn surface widths of the samples, it was found that the sample without diamond has the lower wear resistance than that with diamond. The worn surface width and wear rate for the sample without diamond were obtained as 795 µm and 0.34×10^{-4} mm^3/N.m, respectively.

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

According to the previous study (Pirmohammadi, et al., (2023)), hardness increased from 21.2 to 21.7 GPa by adding 2.5Vol% of diamond reinforcement to the matrix due to the reinforcing effect of diamond particles. Suh increase in 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 was studied using high-magnification SEM images and EDS analysis in more detail.

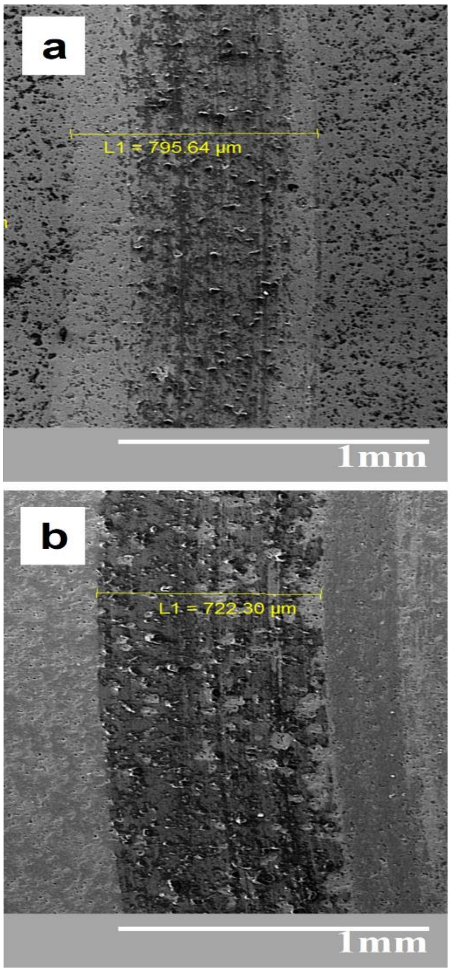


Figure 2. SEM images (Low magnification) of worn surfaces of a) D0, and b) D2.5

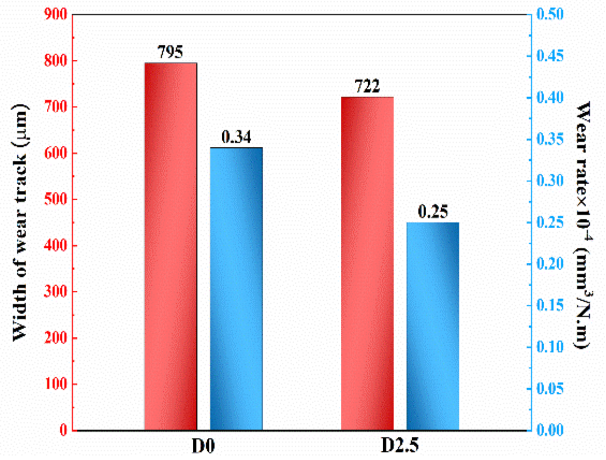
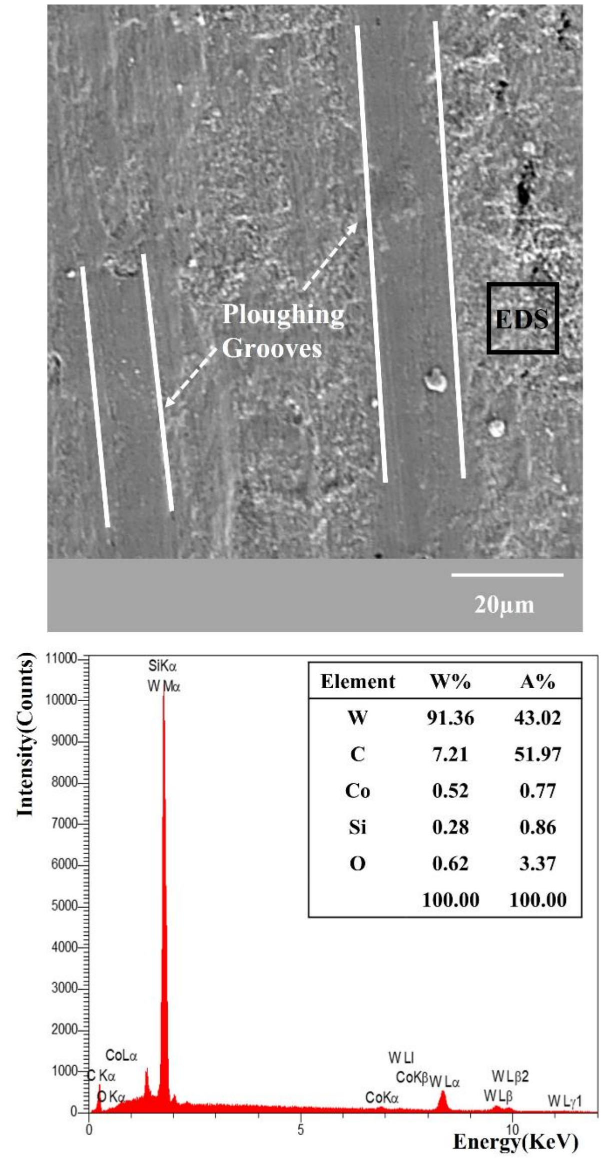


Figure 3. Variation of average width of worn surface, and wear rate for sample contained diamond and sample free diamond

Figure 4 depicts an SEM micrograph of the worn surface of D0 sample where ploughing grooves mechanism in the sliding direction, indicating the abrasive wear throughout the worn surface caused by the continuous movement of high hardness pin on the surface of the sample.



Element	W%	A%
W	91.36	43.02
C	7.21	51.97
Co	0.52	0.77
Si	0.28	0.86
O	0.62	3.37
	100.00	100.00

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

Some of the soft cobalt phase was apparently 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 surface.

EDS analysis confirmed the presence of tungsten, carbon, and cobalt as the sample constituents. 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 then attached to the sample during the interaction. Moreover, there is a small amount of oxygen (approximately 0.62 Wt%), resulting from the partial oxidation during the wear test.

The XRD of the diamond-reinforced composite sample is presented in Figure 5. The primary peaks observed in the sample are attributed to tungsten carbide. 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 lower amount of diamond and cobalt compared to the WC phase.

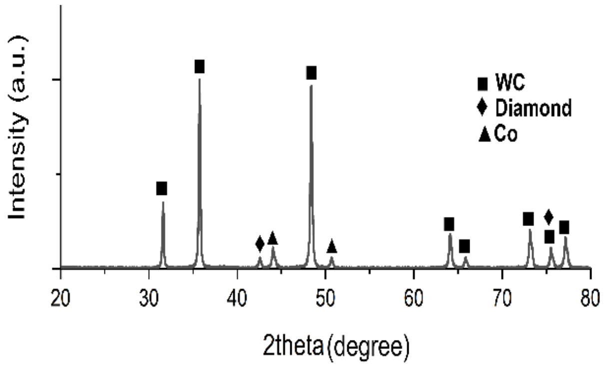


Figure 5. The XRD of D2.5 sample

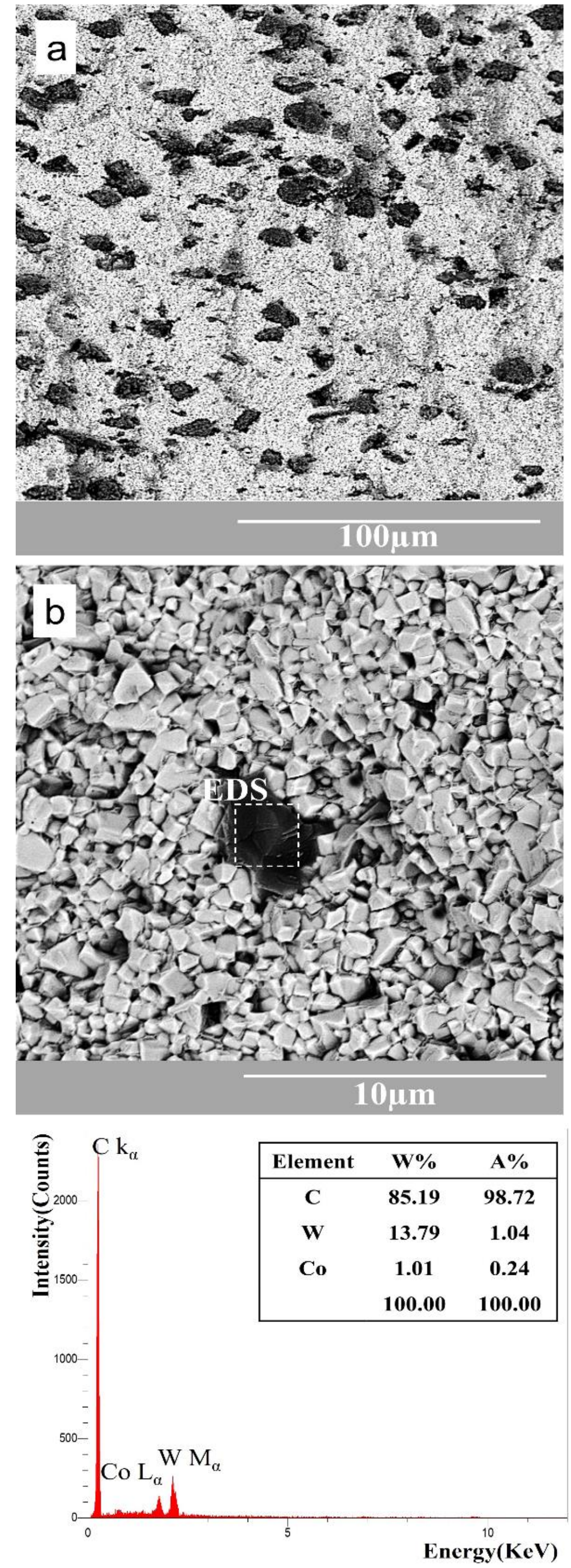
As shown in Figure 6 of the SEM analysis of the fracture surface of the D2.5 sample, a dark phase is evenly distributed in the WC-Co matrix. According to the EDS analysis, this dark phase consists of diamond. The presence of tungsten and cobalt in the EDX spectrum is attributed to the presence of tungsten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

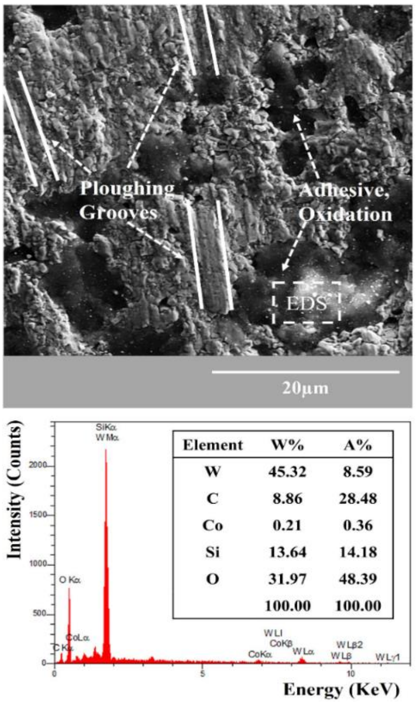
Diamond exhibits higher thermal conductivity than tungsten carbide. This elevated thermal conductivity facilitates increased heat transfer to the sample during wear, unlike the sample without additives. As a result, the temperature of the sample rises more significantly during wear, thereby enhancing 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.



Element	W%	A%
C	85.19	98.72
W	13.79	1.04
Co	1.01	0.24
	100.00	100.00

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



Element	W%	A%
W	45.32	8.59
C	8.86	28.48
Co	0.21	0.36
Si	13.64	14.18
O	31.97	48.39
	100.00	100.00

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

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 would likely lead to the pull out Si from the pin and cause adhesion on the sample surface during the wear process. Hence, addition of diamond to WC-Co composites will result in a change in 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

As illustrated schematically in Figure 8-a, the main wear mechanisms observed in the D0 sample is abrasive mechanisms that 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 involve 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.

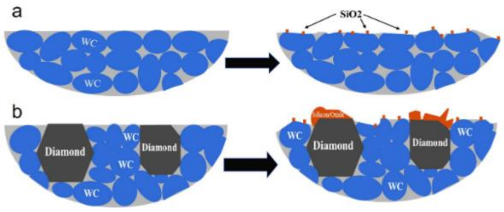


Figure 8. Schematic of wear mechanism in samples a) D0 and b) D2.5

4. CONCLUSION

This study employed SPS method to fabricate WC-Co-2.5 vol.% Diamond and WC-Co samples, and the wear behavior of these samples was examined. The results from wear test confirmed a significant improvement in the wear resistance for the WC-Co sample reinforced with diamond particles, 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 by 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, incorporation of the diamond particles into the WC-Co matrix led to a complete change in the wear mechanism. The reinforced samples were a combination of oxidation, adhesive, and abrasive mechanisms during the wear process. The results revealed that diamond can be effectively used as a reinforcement to enhance the wear resistance of WC-Co composites.

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