Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science. 2026 vol. 28 no. 3 pp. 167–184
ISSN: 1994-6309 (print) / 2541-819X (online)
DOI: 10.17212/1994-6309-2026-28.3-167-184

NSTU NETI

Obrabotka metallov -
Metal Working and Material Science

Journal homepage: http://journals.nstu.ru/obrabotka_metallov

Effect of deep cryogenic treatment duration on microstructure and tribological behaviour of WC-Co cutting tools

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ARTICLE INFO

Article history:
Received: 15 June 2026
Revised: 29 June 2026
Accepted: 11 July 2026
Available online: 15 September 2026

Keywords:
WC-Co cutting tools
Deep cryogenic treatment
Cryogenic soaking duration
Tungsten carbide
Tool wear
Coefficient of friction
Tribological performance
SEM–EDS analysis
Microstructural refinement

ABSTRACT

Introduction. Titanium machining is difficult because of its low thermal conductivity, high chemical affinity, and tendency to generate high cutting-zone temperatures, which accelerate tool wear and premature tool failure. *WC-Co* cutting tools are common to these applications; however, the degree of microstructural stability, the distribution and wear resistance of the cobalt binder play an important role in the performance. The effect of deep cryogenic treatment (*DCT*) soaking time on the tribological properties and the microstructure of *WC-Co* end mill cutting tools is investigated in the present study. **Materials and methods.** *WC-Co* tools were examined under three conditions: untreated (*UT*), 24 h *DCT*, and 36 h *DCT*. The cryogenic treatment was carried out at −196°C with subsequent slow temperature increase and tempering at 150°C for 2 h. To assess tungsten carbide grain distribution, cobalt binder phase continuity and porosity, the microstructural characteristics were studied by optical microscopy (*OM*), scanning electron microscopy (*SEM*) and energy-dispersive spectroscopy (*EDS*). Tribological performance was evaluated using a *Ducom* tribometer in accordance with *ASTM G133*, with wear loss and coefficient of friction as the primary measurement parameters. **Results and discussion.** The 24 h *DCT* sample exhibited the most uniform and fine-grained *WC* structure, a more uniform distribution of the cobalt binder than the untreated sample, and lower porosity than the 36 h *DCT* sample. This microstructural enhancement led to the lowest *COF* of 0.33 and minimum wear loss of 0.138 g. The coefficient of friction for the untreated sample was 0.40, which was higher than that of the treated samples, while the wear loss for the untreated sample was 0.176 g. The 36 h *DCT* sample exhibited intermediate values of the coefficient of friction (0.37) and wear loss (0.157 g); thus, the beneficial effect of cryogenic treatment may be lessened with prolonged soaking time because of the development of defects and microstructural non-uniformity. ***Conclusions.*** The 24 h *DCT* soaking time was determined to be the optimal condition to improve the microstructural stability, friction reduction, and wear resistance of *WC-Co* cutting tools. The results are helpful for determining the parameters for the cryogenic treatment of *WC-Co* cutting tools for use in difficult-to-machine materials like titanium.

For citation: Jagtap K.R., Deshmukh R.R. Effect of deep cryogenic treatment duration on microstructure and tribological behaviour of WC-Co cutting tools. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2026, vol. 28, no. 3, pp. 167–184. DOI: 10.17212/1994-6309-2026-28.3-167-184. (In Russian).

Introduction

Tungsten carbide–cobalt (*WC–Co*) cutting tools are widely applied in machining processes due to their high hardness, compressive strength, hot hardness, and wear resistance [1–3]. In the machining of difficult-to-cut materials, the cutting edge is subjected to intense tribological, mechanical, and thermal loading, which makes these tools crucial. The microstructure of the *WC–Co* product, particularly the distribution of *WC* grains, the continuity of the cobalt binder phase, the porosity, and the concentration of defects, are important factors affecting the performance of *WC–Co* tools [2, 3]. Any kind of instability in these microstructural features can enhance tool wear, increase friction, and reduce tool life during machining.

The excellent high strength-to-weight ratio, corrosion resistance, and biocompatibility of titanium and its alloys allow them to be used widely across the aerospace, biomedical, marine, and chemical industries

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[1, 4–6]. Titanium is a difficult-to-machine material due to its low thermal conductivity, high chemical reactivity, and high heat retention in the cutting area [1, 4, 15]. These characteristics contribute to high interface temperature, adhesion between tool and workpiece, rapid flank wear, and early failure of the cutting tool during machining. Hence, to achieve improved productivity and surface quality during titanium machining, it is necessary to enhance tool wear resistance.

A number of methods have been employed to enhance cutting tool performance such as tool coatings, optimal cutting parameters, advanced cooling strategies, and post-processing treatments [5, 6, 13]. Of these, deep cryogenic treatment (*DCT*) has received a lot of interest as an additional process for cemented carbide cutting tools [7, 8]. Typically, *DCT* is performed by cooling the tool to cryogenic temperatures and allowing it to remain at that temperature for a certain dwell time, after which it is slowly brought back to room temperature. This treatment can affect the residual stress distribution, the stability of the carbide phase, the behavior of the cobalt binder, and the uniformity of the microstructure [2, 9, 10]. Consequently, suitable conditions of cryogenic treatment can enhance the hardness, wear resistance, dimensional stability, and tribological properties [16, 18–20].

The application of deep cryogenic treatment depends on various process parameters, including cooling rate, soaking temperature, soaking time, warming rate, and tempering after deep cryogenic treatment [7, 8, 11]. Of these parameters, soaking duration is critical [7, 8, 11]. Insufficient soaking time can result in inadequate modification of the microstructure, while excessive soaking time can result in microstructural non-uniformity, binder phase instability, and/or increased formation of defects. Therefore, it is necessary to determine the optimum soaking time that provides maximum improvement in wear resistance without over-treatment [20–23].

A number of researchers have found that cryogenic treatment of cemented carbide tools for machining difficult materials has beneficial effects [1, 5, 12, 17]. Refined microstructure, improvements in binder distribution, and defect minimization typically have been correlated with improved wear resistance and tool life [10, 19, 20]. However, there is no adequate comparative knowledge of the effect of different *DCT* soaking durations on the microstructure and tribological response of *WC–Co* end mill cutters in the literature [7, 8, 11]. Specifically, the correlation between optical microscopy, *SEM–EDS* observation, coefficient of friction, and wear loss is still limited [10, 19, 20]. This gap limits the choice of appropriate cryogenic treatment process parameters in practical machining applications.

In the present study, two different deep cryogenic soaking times – 24-h and 36 h – were used for *WC–Co* end mill cutters, and they were compared with their untreated counterparts. The microstructural changes were investigated by optical microscopy, scanning electron microscopy, and energy-dispersive spectroscopy [1, 12, 20]. Tribological behavior was studied using a tribometer in accordance with *ASTM G133*. This study focuses on the relationship between the observed microstructural features and wear loss and coefficient of friction, and determines the optimal duration of cryogenic soaking treatment.

Several researchers have reported improvements in the wear resistance, hardness, and tribological behavior of *WC–Co* cutting tools after deep cryogenic treatment [1, 7, 8, 10, 20]. However, few studies have investigated the effect of cryogenic soaking duration on the microstructural changes and tribological properties of *WC–Co* end mill cutters [8, 11, 20]. Additionally, there are no well-established links between grain distribution, the continuity of the cobalt binder phase, porosity characteristics, and tribological performance [10, 19, 20]. Therefore, an experimental study is needed to ascertain the effect of soaking time on microstructural stability and wear performance.

The purpose of this study is to investigate the effect of deep cryogenic treatment soaking duration on the microstructure and tribological behavior of *WC–Co* cutting tools.

The specific objectives of the study are as follows:

1. To deep cryogenically treat *WC–Co* end mill cutters for soaking times of 24-h and 36 h.

2. To study the microstructural changes in the untreated and cryogenically treated WC–Co tools using optical microscopy, *SEM*, and *EDS*.

3. To investigate the influence of the soaking duration of *DCT* on wear loss and the coefficient of friction in accordance with *ASTM G133*.

4. To correlate the distribution of *WC* grains, cobalt binder phase behavior, and porosity with tribological performance.

5. To determine the optimal cryogenic soaking time for enhancing wear resistance and minimizing frictional forces in *WC–Co* cutting tools.

Materials and methods

Workpiece and cutting tool material

The workpiece material used in the machinability evaluation was commercially pure titanium (Fig. 1). Commercial solid tungsten carbide–cobalt (*WC–Co*) end mill cutters were used in this investigation (Fig. 2). The cutting tools were made of cemented carbide, which is composed of a very fine-grained matrix of about 10 wt.% cobalt binder and 90 wt.% tungsten carbide. The mean grain size of the *WC* was about 0.8–1.5 µm. The end mill cutters used were 4-fluted, with a diameter of 10 mm. The selected *WC–Co* grade is highly likely used for the machining of titanium alloys owing to its high hardness, good wear resistance, and good hot hardness. All tools were purchased from the same production batch to ensure the same material composition and microstructural characteristics before deep cryogenic treatment.

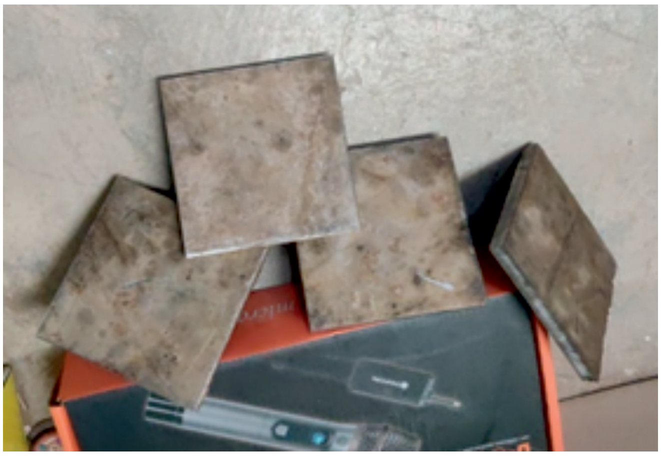


Fig. 1. Commercially pure titanium workpiece material used in the study

Fig. 2. WC-Co end mill cutters used in the investigation

Deep cryogenic treatment

The influence of soaking time on the tribological behavior and microstructure of *WC–Co* cutting tools was investigated via deep cryogenic treatment (Fig. 3). Untreated tools were used as reference samples. The tools subjected to cryogenic treatment were soaked in liquid nitrogen at approximately −196 °C. The cryogenic treatment cycle consisted of controlled cooling, soaking, controlled warming, and tempering. The specimen machining conditions are listed in Table 1.

The tools were cooled from room temperature to −196 °C at an average cooling rate of about 1 °C/min. The samples were then soaked for 24-h or 36 h after reaching the target temperature. The samples were subsequently warmed to room temperature at a controlled rate to avoid thermal shock. Residual stresses generated during the cryogenic treatment were subsequently removed by tempering at 150 °C for 2 h.

Wear testing

Tribological tests were carried out using a *Ducom* tribometer in accordance with *ASTM G133* (Fig. 4). The test parameters are given in Table 2. Cylindrical samples were taken from each treatment group for wear testing. The diameter of each sample was 10 mm, and the length was 14 mm. The tests were performed under dry sliding conditions. Before testing, the samples were cleaned and weighed using an electronic balance. After the tests, the samples were cleaned again, dried, and weighed again. The mass

Fig. 3. Deep cryogenic treatment setup used for WC-Co cutting tools

Table 1

Deep cryogenic treatment conditions used for *WC–Co* cutting tools

Sample designation	Treatment condition	Soaking temperature (°C)	Soaking duration (h)	Tempering condition
UT	Untreated	–	0	–
24-h DCT	Deep cryogenic treatment	−196	24	150°C for 2 h
36-h DCT	Deep cryogenic treatment	−196	36	150°C for 2 h

Fig. 4. Ducom tribometer used for linearly reciprocating sliding wear testing

Table 2

Wear test parameters

Parameter	Value
Test standard	*ASTM G133*
Tribometer	*Ducom* tribometer
Test temperature	200°C
Normal load	30 N
Test duration	30 min
Stroke length	30 mm
Frequency	3–5 Hz
Sample diameter	10 mm
Sample length	14 mm
Test condition	Dry sliding

difference was used to determine wear loss. The coefficient of friction was recorded during each test, and the average coefficient of friction was determined for each treatment condition.

Wear loss was calculated using the following equation:

$$\text{Wear loss} = \text{Initial weight} - \text{Final weight}$$

For a more complete tribological assessment, the specific wear rate can be calculated using the equation:

$$\text{Specific wear rate} = \Delta \boldsymbol{V} / (\boldsymbol{F} \times \boldsymbol{L})$$

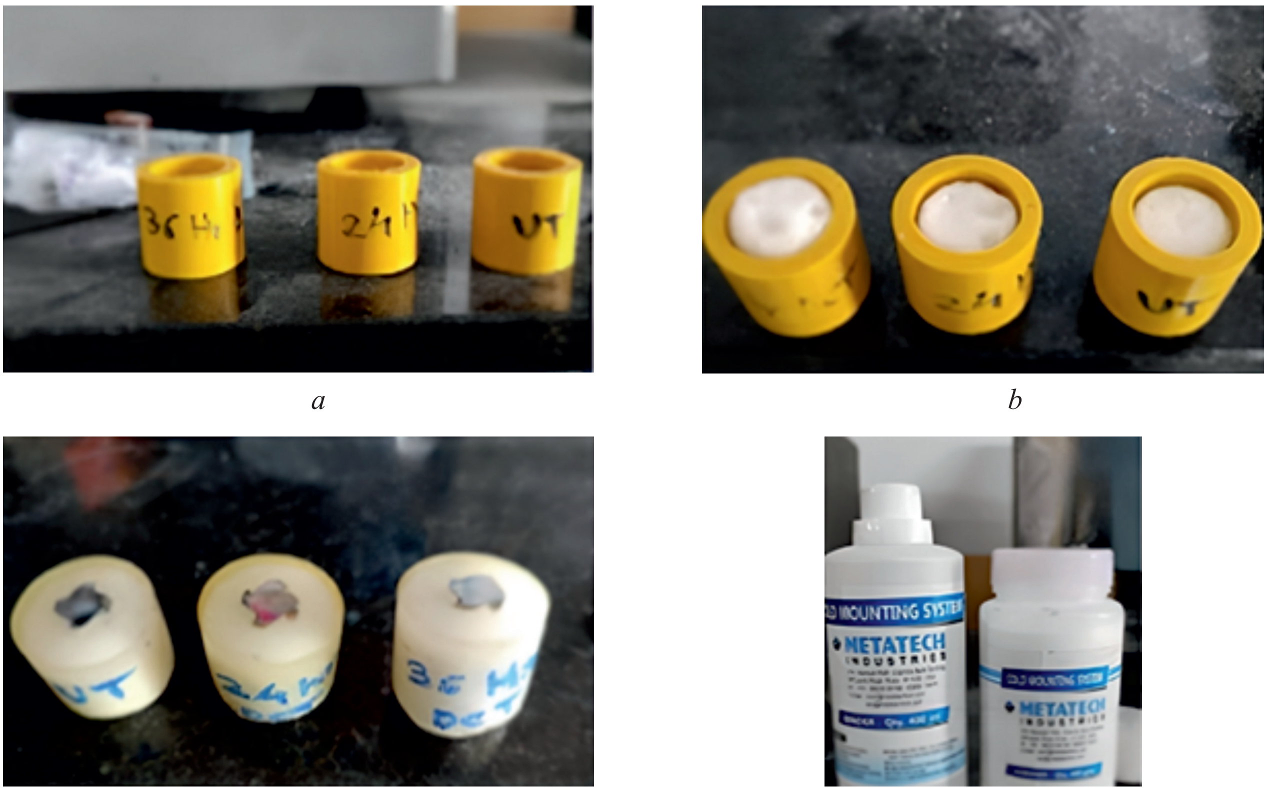
where $\boldsymbol{\Delta V}$ is the volume loss (mm^3); $\boldsymbol{F}$ is the applied load (N); $\boldsymbol{L}$ is the sliding distance (m); The volume loss can be obtained from mass loss and material density.

Sample preparation for microstructural characterization

The *WC–Co* tool samples were prepared according to conventional metallographic methods prior to microstructural characterization (Fig. 5). Each end mill cutter was sectioned by precision wire cutting to obtain a sample of about 5 mm from the cutting edge. Cold mounting was carried out in mounting resin to facilitate handling during grinding and polishing.

The mounted samples were ground with abrasive papers of successively finer grit sizes: 400, 600, 800, 1,000, and 1,200 grit. After grinding, the samples were polished with diamond paste to obtain a mirror-like finish. The polished samples were then chemically etched with *Murakami's* reagent, consisting of 10 g of potassium ferricyanide, 10 g of potassium hydroxide, and 100 mL of distilled water. The etching time was approximately 30 s. After etching, the samples were cleaned in ethanol and then dried in hot air.

The preparation procedure described above was employed to reveal tungsten carbide grains and the cobalt binder phase. The prepared samples were subsequently examined by optical microscopy, *SEM*, and *EDS*.



a *b* *c* *d*

Fig. 5. Sample preparation procedure for microstructural characterization:
a – sectioned WC-Co tool sample; *б* – cold-mounted sample; *в* – ground and polished sample; *г* – etched sample ready for microscopic examination

Optical microscopy

Optical microscopy was used to characterize the general microstructural features of untreated and cryogenically treated *WC–Co* samples. The analysis focused on *WC* grain distribution, apparent porosity, cobalt binder continuity, and visible microstructural defects. The optical micrographs were used for comparative evaluation of the *UT*, 24-h *DCT*, and 36-h *DCT* samples.

Scanning electron microscopy and energy-dispersive spectroscopy

Scanning electron microscopy was used to examine the microstructural morphology of the *WC–Co* samples at higher magnification. *SEM* observations were performed to study the distribution of tungsten carbide grains, cobalt binder regions, microvoids, porosity, and defect formation. Energy-dispersive spectroscopy was used to verify the elemental composition and phase distribution of the samples.

SEM–EDS analysis was performed on the *UT*, 24-h *DCT*, and 36-h *DCT* samples. The untreated sample was used as the baseline condition. The 24-h *DCT* sample was examined to assess the effect of cryogenic soaking on microstructural refinement and binder distribution. The 36-h *DCT* sample was examined to identify possible microstructural non-uniformity or over-treatment effects.

Results and discussion

The results of the EDS analysis of the elemental composition of the specimens are given in Table 3. The contents of the main elements (W, C, Co, O) are similar in all three states, which indicates that the chemical composition of the cemented carbide is retained after cryogenic treatment; the observed differences lie within the accuracy of the method and reflect mainly a redistribution of phases rather than a change in the average composition.

Table 3

EDS elemental composition of _WC–Co_ samples

Sample	*W* (wt.%)	*C* (wt.%)	*Co* (wt.%)	*O* (wt.%)
UT	82.5	7.8	9.1	0.6
24-h *DCT*	82.8	7.9	8.8	0.5
36-h *DCT*	82.3	7.7	9.3	0.7

The *EDS* analysis confirmed the presence of tungsten, carbon, and cobalt in all samples. The 24-h *DCT* sample exhibited a more uniform elemental distribution compared with the untreated and 36-h *DCT* conditions, indicating improved phase stability and binder homogeneity.

Microstructural characterization

Microstructural characterization was conducted to assess the impact of deep cryogenic treatment (*DCT*) on the internal structure of tungsten carbide–cobalt (*WC–Co*) cutting tools. Three tool conditions (untreated (*UT*), 24-h *DCT*, and 36-h *DCT*) were analyzed. The main aim was to investigate changes in grain size, the distribution of the cobalt binder, and porosity, which directly affect the tool wear resistance and performance.

Optical microscopy (OM) analysis

The general microstructural characteristics of the prepared samples were examined using optical microscopy. The observations showed clear differences between the three conditions. The untreated sample had a comparatively non-uniform distribution of tungsten carbide grains and apparent porosity. The 24-h *DCT* sample, in contrast, exhibited a fine and well-dispersed grain structure with much less porosity and enhanced connectivity of the cobalt binder phase. The 36-h *DCT* sample showed slight grain coarsening and non-uniform distribution, indicating the beginning of over-treatment.

Untreated sample (Fig. 6 a)

In the untreated sample, the tungsten carbide (*WC*) grains in the cobalt (*Co*) binder matrix were relatively homogeneous. However, red spots indicated the presence of porosity, inclusions, or binder-rich areas. The *WC* grains were fine and well dispersed, and no marked abnormal grain growth was observed. The cobalt binder phase was continuous, implying a well-sintered structure. Nevertheless, some defect concentration was observed, indicating the presence of original microstructural flaws.

24-h *DCT sample (Fig. 6 b)*

The 24-h cryogenically treated sample showed a marked microstructural improvement. The *WC* grains were also well dispersed and densely packed, indicating that the grains had been refined. The number of red regions was reduced, implying lower porosity and fewer defects. The cobalt binder phase was more uniform and evenly distributed, which increases structural integrity. Moreover, the visibility of *WC* grain dominance was enhanced, suggesting better phase distribution as a result of the cryogenic treatment.

36-h DCT sample (Fig. 6 c)

The 36-h *DCT* sample showed signs of over-treatment. Although the presence of *WC* grains was observed, the microstructure was less homogeneous than that of the 24-h sample. A greater number of red regions (defects and porosity) was observed, indicating deteriorated microstructural quality. The cobalt binder phase was found to be more discontinuous, suggesting possible binder coarsening.

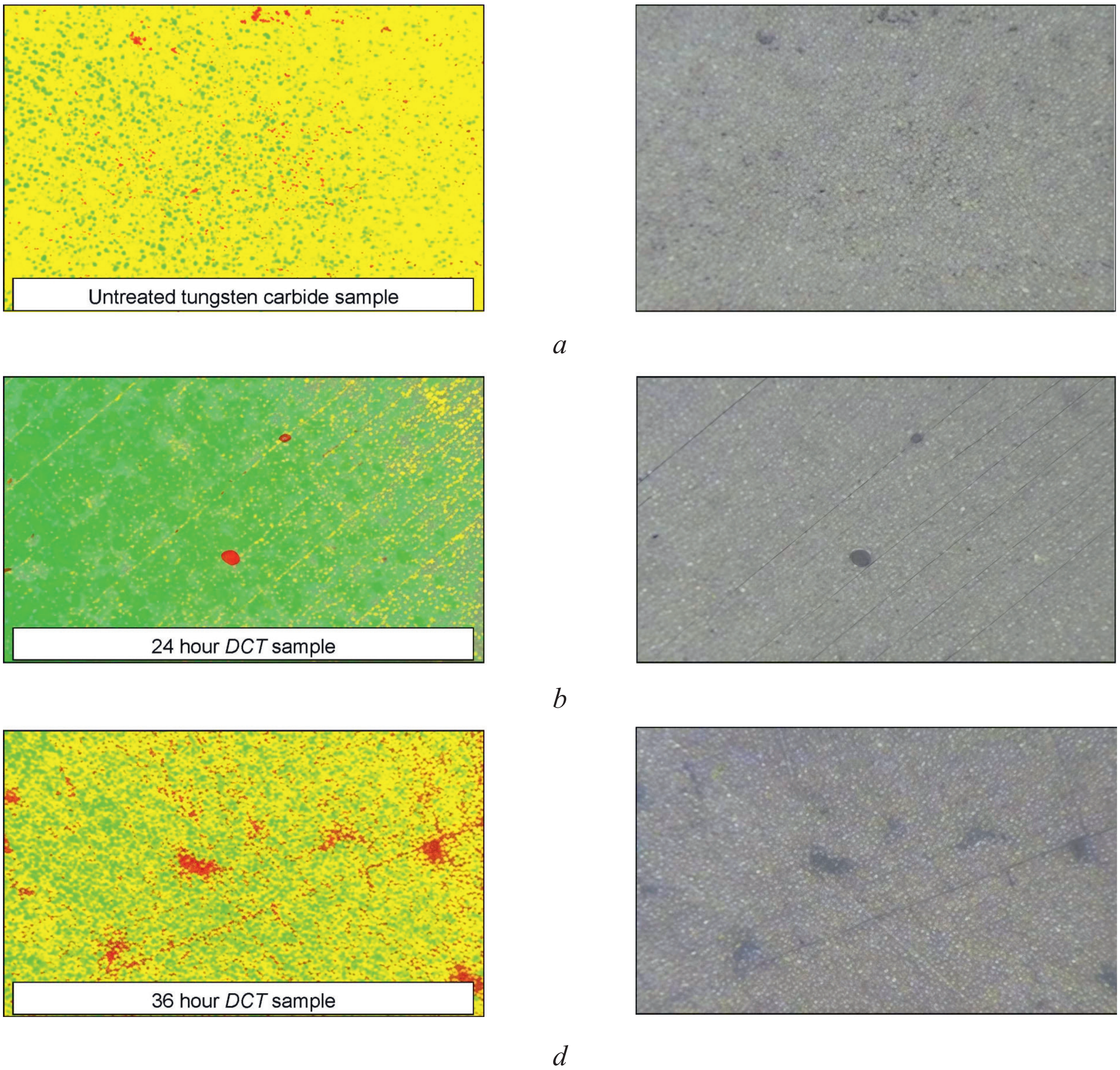


Fig. 6. Optical microscopy images of *WC–Co* cutting tools before machining:
a – untreated sample; *b* – 24-hour *DCT* sample; *c* – 36-hour *DCT* sample

Scanning electron microscopy with energy dispersive spectroscopy analysis

These results suggest that excessive cryogenic soaking leads to reduced microstructural stability. Scanning electron microscopy (*SEM*) and energy-dispersive spectroscopy (*EDS*) were performed to characterize the microstructural morphology and elemental composition of tungsten carbide–cobalt (*WC–Co*) cutting tools prior to machining. Three tool conditions were analyzed: untreated (*UT*), 24-h *DCT*, and 36-h *DCT*. *SEM* was used to obtain high-resolution images of tungsten carbide grains, cobalt binder distribution, and defects, whereas *EDS* was used to verify the elemental composition and phase uniformity of the samples.

SEM–EDS analysis of the untreated sample (Fig. 7 a)

The *SEM* micrograph of the untreated sample showed irregular polygonal *WC* grains closely packed with clear grain boundaries. The tungsten carbide phase was represented by darker areas, whereas the cobalt (*Co*) binder phase was represented by the lighter grey network around the grains. The binder phase was reasonably continuous, indicating good sintering conditions. However, some isolated dark areas and microvoids were observed, indicating porosity, pull-outs, or binder-depleted areas. Such flaws may be formed during polishing or as a result of incomplete densification during sintering. The overall microstructure is characteristic of a fine-to-medium grain *WC–Co* composite with moderate phase contrast.

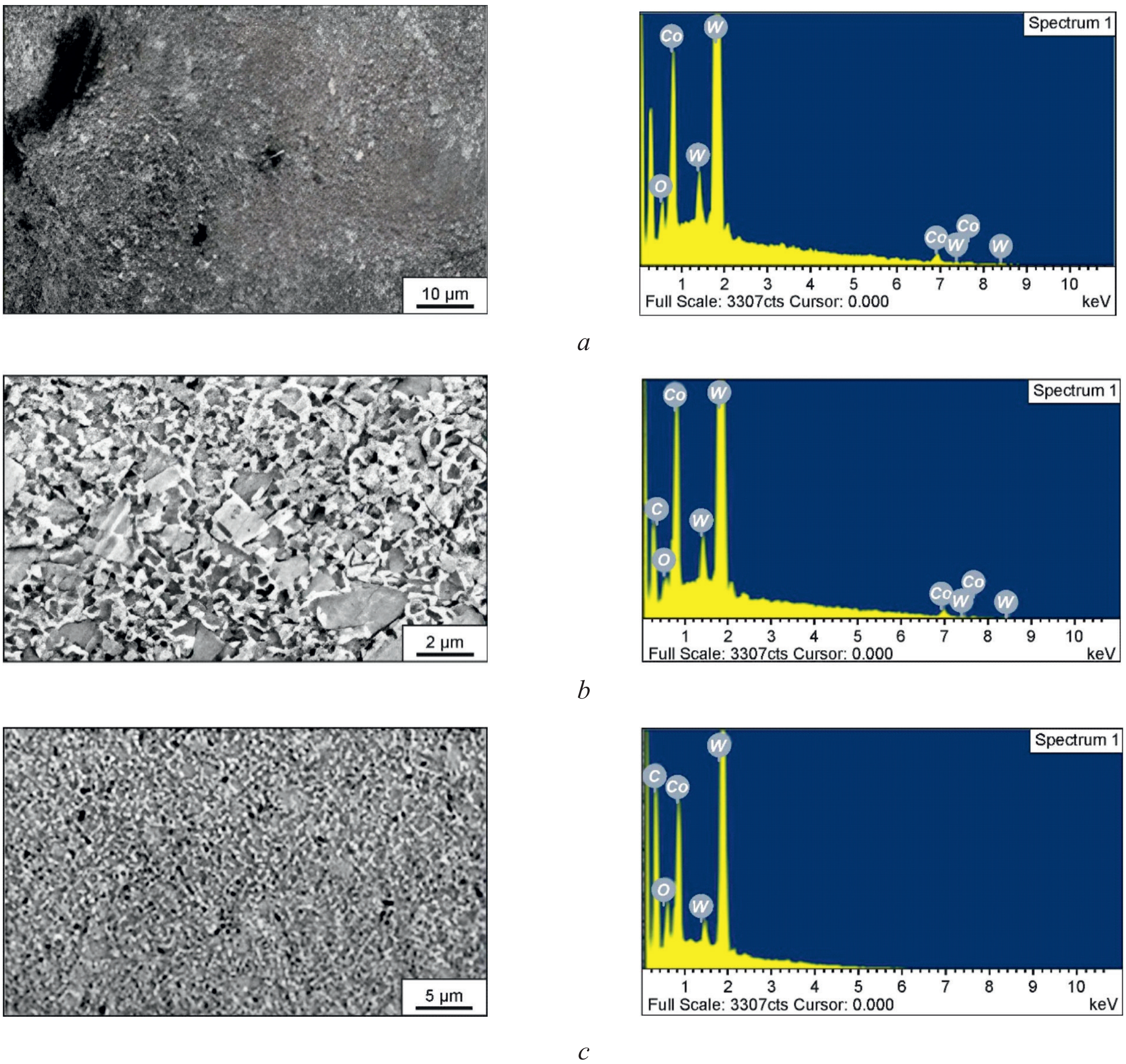


Fig. 7. Microstructure and *SEM–EDS* analysis results of the *WC–Co* sample:
a – in the untreated condition; *b* – after 24-h of *DCT* treatment; *c* – after 36 h of *DCT* treatment

Interpretation

The untreated sample exhibits a stable and moderately refined microstructure with acceptable grain distribution and binder continuity. However, porosity and defects may be detrimental to wear resistance and mechanical performance, as observed during machining.

SEM–EDS analysis of 24-h *DCT sample (Fig. 7 b)*

The *SEM* microstructure of the 24-h *DCT* sample showed a high degree of *WC* grain refinement: the grains were smaller, more evenly distributed, and more tightly packed than in the untreated sample. The grain boundaries were more pronounced and defined, indicating enhanced interfacial bonding and improved microstructural stability. The cobalt binder phase exhibited a higher degree of homogeneity and less pooling, suggesting better wetting and redistribution of the binder between *WC* grains. In addition, porosity and defects were low, indicating lower internal stresses and enhanced densification as a result of the cryogenic treatment. *EDS* analysis confirmed the presence of tungsten (*W*), cobalt (*Co*), and carbon (*C*), along with a more uniform element distribution, confirming the microstructural changes observed.

Interpretation

The 24-h *DCT* sample exhibits optimal microstructural characteristics, including grain refinement, uniform binder distribution, and reduced porosity. These features contribute to improved structural integrity, which is expected to enhance wear resistance, reduce friction, and increase tool life.

SEM–EDS analysis of 36-h DCT sample (Fig. 7 c)

The *SEM* micrograph of the 36-h *DCT* sample showed coarser *WC* grains compared with the 24-h sample. The grains still retained their angular morphology, but some grain boundaries were less distinct in certain areas, indicating the beginning of grain boundary relaxation. The cobalt binder phase was partially segregated and localized, suggesting thermally activated migration during prolonged cryogenic exposure. In addition, moderate porosity and microvoids were observed, which were greater than in the 24-h *DCT* sample but still less than in the untreated condition. The elemental composition was confirmed by *EDS* analysis, which revealed slight variations in phase distribution, attributed to binder segregation and microstructural defects.

Interpretation

The 36-h *DCT* sample shows signs of over-treatment, including grain coarsening, binder phase segregation, and a higher density of defects compared with the 24-h *DCT* sample. Although it performs better than the untreated sample, it lacks the optimal microstructural balance required for superior performance.

The *SEM–EDS* analysis clearly showed that deep cryogenic treatment has a strong impact on the microstructure of *WC–Co* cutting tools. The 24-h *DCT* sample exhibited the most desirable combination of properties: refined grain structure, evenly dispersed binder, and low porosity compared with the other two conditions. The 36-h *DCT* sample showed diminishing benefits, indicating that excessive soaking time leads to microstructural degradation.

Wear analysis

The cutting tools were tested using a tribometer under dry sliding conditions to evaluate wear performance. Before and after testing, the weight of each sample was determined using a precision electronic balance (*Kero Laboratory Scale*, Model *BL-P6D/5003*, with a resolution of 0.001 g). Wear loss and wear resistance were calculated from the weight difference. The tested samples had a diameter of 10 mm and a length of 14 mm. Fig. 8 shows the experimental setup and weight measurements before and after the test.

Tribological results showed (Table 4) that the 24-h *DCT* sample exhibited the lowest wear loss (0.138 g), which represents a decrease of about 21.6% compared with the untreated sample. This enhanced wear resistance is attributed to grain refinement, improved cobalt binder distribution, and reduced porosity. The 36-h *DCT* sample showed intermediate results, suggesting that longer soaking durations may be undesirable, as they diminish the beneficial effects gained from shorter soaking durations.

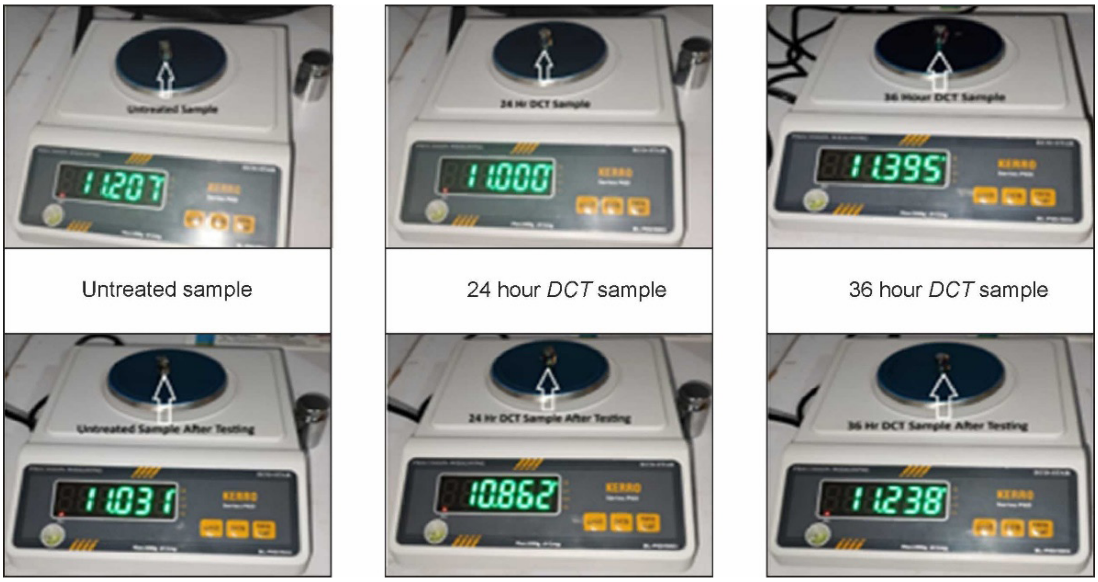


Fig. 8. Weighing of samples before and after wear testing

Table 4

Wear test results

Sample	Initial mass (g)	Final mass (g)	Mass loss (g)
Untreated	11.207	11.031	0.176
24-h DCT	11.000	10.862	0.138
36-h DCT	11.395	11.238	0.157

The improved wear resistance in the 24-hour *DCT* sample is attributed to:
– refined *WC* grain structure,
– uniform cobalt binder distribution,
– reduced porosity and defects.

These properties enhance load-bearing capacity and reduce material removal during sliding. Conversely, the 36-hour *DCT* sample exhibited slightly more wear than the 24-hour sample due to grain coarsening and binder segregation, as observed in *SEM* analysis. It performs better than the untreated sample, but excessive cryogenic exposure leads to reduced microstructural stability.

Coefficient of friction (COF) analysis

The *COF* data clearly show (Table 5) that deep cryogenic treatment had a positive effect on tribological performance. The 24-h *DCT* condition exhibited the lowest average coefficient of friction (0.33), which is about 17.5% lower than that of the untreated sample (0.40). This improvement is attributed to microstructural homogenization and reduced surface roughness.

Quantitative porosity analysis

Optical micrographs of the untreated and deep cryogenically treated *WC–Co* samples were analyzed using the image-processing software *ImageJ* for quantitative porosity analysis. The micrographs were converted to grayscale images and threshold-segmented to differentiate pore regions from the matrix. The porosity percentage was determined by dividing the total pore area by the total analyzed area. For each sample, multiple micrographs were analyzed, and the average was reported to increase the reliability of the measurements.

The quantitative porosity analysis showed (Table 6) that deep cryogenic treatment had a significant effect on reducing porosity. The *UT* sample had the highest porosity of 3.42%, indicating the presence

Table 5

Average coefficient of friction

Sample	Average coefficient of friction
UT	0.40
24-h DCT	0.33
36-h DCT	0.37

Table 6

Porosity of *WC–Co* samples

Sample	Porosity (%)
UT	3.42
24-h DCT	1.86
36-h DCT	2.47

of microvoids and discontinuities in the *WC–Co* matrix. In contrast, the lowest porosity value of 1.86% was observed for the 24-h *DCT* sample, indicating microstructural densification and a more uniform distribution of the cobalt binder phase. The intermediate porosity value for the 36-h *DCT* sample (2.47%) suggests that extended cryogenic soaking may result in diminished positive effects compared with 24-h soaking. Reduced porosity leads to a higher load-bearing capacity, fewer stress concentration regions, and better wear resistance, which is consistent with the tribological findings of the present investigation. The superior performance of the 24-h *DCT* sample is therefore partly attributed to its lower porosity and better microstructural integrity.

Discussion

The *COF* findings clearly show that the average coefficient of friction is lowest for the 24-h *DCT* sample (0.33), and the frictional behavior is also most stable over the course of the test. Conversely, the untreated sample exhibits the highest *COF* (0.40), which fluctuates more, indicating unstable sliding conditions.

The 36-h *DCT* sample exhibits intermediate friction behavior (0.37), performing better than the untreated sample but not as well as the 24-h *DCT* sample. Fig. 9 shows the friction coefficient as a function of test time. The superior performance of the 24-h *DCT* sample can be attributed to its smooth and homogeneous microstructure, as confirmed by *OM* and *SEM*.

Improved distribution of tungsten carbide grains and the cobalt binder phase helps to minimize surface irregularities and improves load distribution, thereby reducing friction. The untreated sample exhibits higher friction due to microstructural defects, porosity, and non-uniform grain distribution, which increase resistance during sliding.

Binder phase segregation and grain coarsening cause the 36-h *DCT* sample to exhibit slightly higher friction than the 24-h *DCT* sample, indicating the beginning of over-treatment. Moreover, the 24-h *DCT* sample exhibits stable friction behavior over time, which is critical for high-performance machining and low heat generation. Reduced friction directly reduces tool–workpiece interaction forces and enhances tool life.

The findings clearly indicate that deep cryogenic treatment is an important process for improving the wear resistance and tribological behavior of *WC–Co* cutting tools. However, soaking time is highly sensitive with respect to the effectiveness of the treatment. The 24-h *DCT* condition offers the best balance between grain refinement and structural stability, resulting in superior performance. Conversely, excessive treatment (36 h) leads to a diminution of benefits due to microstructural degradation.

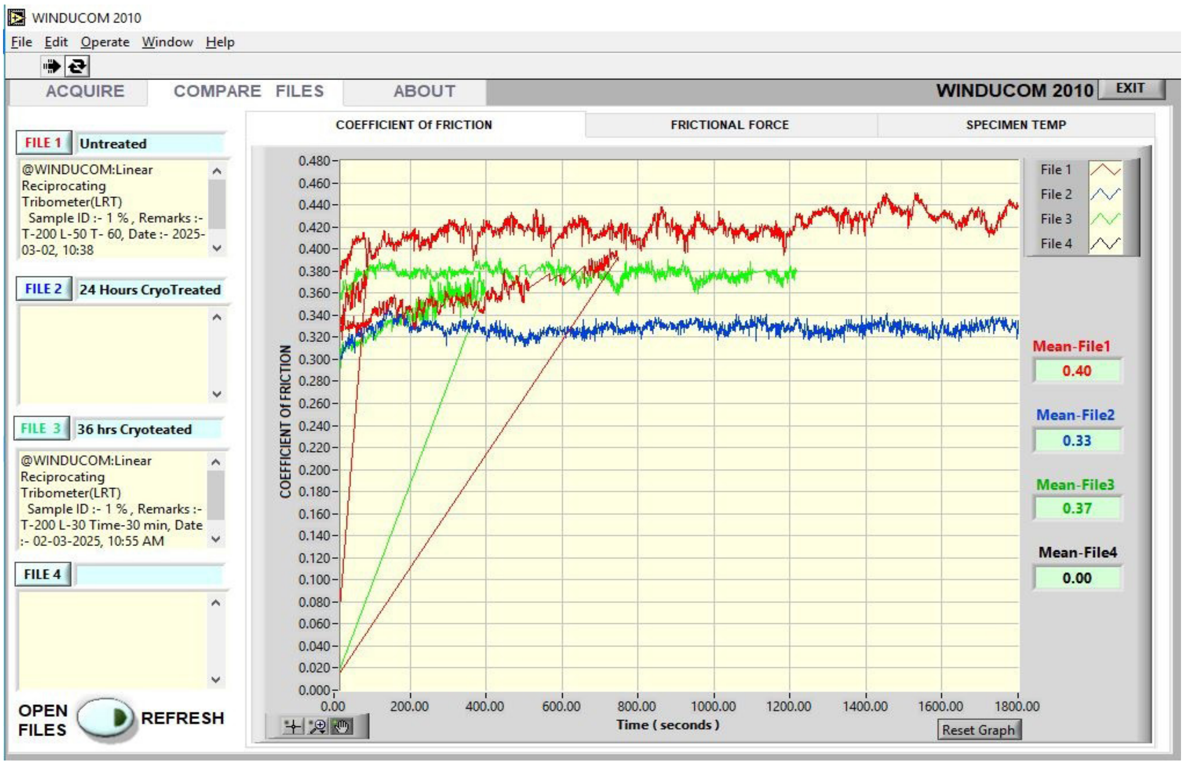


Fig. 9. Coefficient of friction vs. time for untreated, 24-h DCT, and 36-h *DCT* samples

Conclusion

The influence of soaking duration during deep cryogenic treatment (*DCT*) on the microstructure and tribological behavior of *WC–Co* end mill cutters was investigated.

1. The *WC–Co* tools exhibited significant microstructural changes after deep cryogenic treatment, including improved tungsten carbide grain distribution, improved cobalt binder continuity, and reduced porosity.

2. The microstructure of the 24-h *DCT* sample was the most homogeneous and refined among those studied by optical microscopy and scanning electron microscopy (*SEM*).

3. The 24-h *DCT* sample exhibited the lowest wear loss (0.138 g), whereas the untreated and 36-h *DCT* samples exhibited 0.176 g and 0.157 g, respectively, confirming that the 24-h *DCT* sample had the best wear resistance.

4. The 24-h *DCT* sample exhibited the lowest coefficient of friction (0.33), indicating better tribological properties.

5. The 36-h *DCT* condition revealed microstructural non-uniformity, such as cobalt binder segregation and a higher defect density than that observed for the 24-h *DCT* condition.

6. A positive correlation was confirmed between microstructural refinement and the tribological properties of cryogenically treated *WC–Co* cutting tools.

7. The 24-h *DCT* condition was found to be the best compromise in terms of wear resistance, friction level, and microstructural stability among the conditions tested.

References

1. Celik O.N., Sert A., Gasan H., Ulutan M. Effect of cryogenic treatment on the microstructure and the wear behavior of WC–Co end mills for machining of Ti6Al4V titanium alloy. *The International Journal of Advanced Manufacturing Technology*, 2018, vol. 95 (5–8), p. 2989–2999. DOI: 10.1007/S00170-017-1444-1.

2. Li B., Zhang S., Zhang T., Zhang J. Effect of deep cryogenic treatment on microstructure, mechanical properties and machining performances of coated carbide tool. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 2019, vol. 41 (1). DOI: 10.1007/S40430-018-1533-6.

3. Xie C.H., Huang J.W., Tang Y.F., Gu L.N. Effects of deep cryogenic treatment on microstructure and properties of WC–11Co cemented carbides with various carbon contents. *Transactions of Nonferrous Metals Society of China*, 2015, vol. 25 (9), pp. 3023–3028. DOI: 10.1016/S1003-6326(15)63929-2.

4. Sivalingam V., Sun J., Selvam B., Murugasen P.K., Yang B. Experimental investigation of tool wear in cryogenically treated insert during end milling of hard Ti alloy. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 2019, vol. 41 (2). DOI: 10.1007/S40430-019-1612-3.

5. Bhople N., Mastud S., Mittal R.K. Metallurgical and machining performance aspects of cryotreated tungsten carbide micro end mill cutters. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 2022, vol. 237 (3), pp. 492–502. DOI: 10.1177/09544054221101765.

6. Mastud S., Bhople N., Mittal R.K. Performance analysis of uncoated, TiN coated and cryotreated micro tungsten carbide tools while micromilling of Ti–6Al–4V. *International Journal of Machining and Machinability of Materials*, 2022, vol. 24 (1–2), pp. 110–131. DOI: 10.1504/IJMMM.2022.10044694.

7. Kursuncu B. Influence of cryogenic heat treatment soaking period and temperature on performance of sintered carbide cutting tools in milling of Inconel 718. *International Journal of Refractory Metals & Hard Materials*, 2020, vol. 92. DOI: 10.1016/j.ijrmhm.2020.105323.

8. Arunkarthikeyan K., Balamurugan K., Rao P.M.V. Studies on cryogenically treated WC–Co insert at different soaking conditions. *Materials and Manufacturing Processes*, 2020, vol. 35 (5), pp. 545–555. DOI: 10.1080/10426914.2020.1726945.

9. Varghese V., Ramesh M., Chakradhar D. Influence of deep cryogenic treatment on performance of cemented carbide (WC–Co) inserts during dry end milling of maraging steel. *Journal of Manufacturing Processes*, 2019, vol. 37, pp. 242–250. DOI: 10.1016/j.jmapro.2018.11.030.

10. Sahoo B.N., Mohanty A., Gangopadhyay S., Vipindas K. An insight into microstructure and machining performance of deep cryogenically treated cemented carbide inserts. *Journal of Manufacturing Processes*, 2020,b vol. 58, pp. 819–831. DOI: 10.1016/j.jmapro.2020.09.001.

11. Arunkarthikeyan K., Balamurugan K. Studies on the impact of soaking time on a cryogenic processed and post-tempered WC–Co insert. *Materials Today: Proceedings*, 2021, vol. 44, pp. 1692–1699. DOI: 10.1016/j.matpr.2020.11.869.

12. Chinnasamy M., Rathanasamy R., Palaniappan N., Pal S.K. Microstructural transformation analysis of cryogenic treated conical rock cutting bits for mining applications. *International Journal of Refractory Metals and Hard Materials*, 2022, vol. 110. DOI: 10.1016/j.ijrmhm.2022.105995.

13. Ozbek N. Effects of cryogenic treatment types on the performance of coated tungsten tools in the turning of AISI H11 steel. *Journal of Materials Research and Technology*, 2020, vol. 9, pp. 9442–9456. DOI: 10.1016/j.jmrt.2020.03.038.

14. Mukkoti V.V., Sankaraiah G., Yohan M. Effect of cryogenic treatment of tungsten carbide tools on cutting force and power consumption in CNC milling process. *Production & Manufacturing Research*, 2018, vol. 6, pp. 149–170. DOI: 10.1080/21693277.2018.1436011.

15. Akıncıoğlu S., Gökkaya H., Uygur İ. The effects of cryogenic-treated carbide tools on tool wear and surface roughness of turning of Hastelloy C22 based on Taguchi method. *The International Journal of Advanced Manufacturing Technology*, 2016, vol. 82, pp. 303–314. DOI: 10.1007/s00170-015-7356-z.

16. Sasi J.C., Mathew J., George A., Kuriachen B., Dhanish P.B. Wear behaviour of deep cryogenically treated coated tool during end milling. *SSRN*, 2024. DOI: 10.2139/ssrn.4703707.

17. Chinnasamy M., Samanta B., Kumar R., Rathanasamy R. Next-generation tungsten carbide cutting bits through cryogenic treatment technique for superior rock cutting performance: An experimental study. *International Journal of Refractory Metals and Hard Materials*, 2024, vol. 125. DOI: 10.1016/j.ijrmhm.2024.106923.

18. Prem Chand R., Reddy T.V.S., Anjinappa C., Omprakash B., Razak A., Wodajo A.W. Impact of cryogenic treatment on the performance of coated tungsten carbide inserts during machining of EN24 grade alloy steel. *Engineering Reports*, 2024, vol. 6, p. e12839. DOI: 10.1002/eng2.12839.

19. Biermann J., Bień C.E., Lechte C., Kanzow P., Wiegand A. Dentin bond strength of dental adhesives functionalized with polyhedral oligomeric silsesquioxanes. *Materials*, 2024, vol. 17 (6), p. 1321. DOI: 10.3390/ma17061321.

20. Premjarunan S., Chindaprasirt P., Chaysuwan D. Study on the effects of cryogenic treatment on WC–Co cemented carbides. *Metals*, 2025, vol. 15 (3), p. 297. DOI: 10.3390/met15030297.

21. Mao P., Peng J., Chen K., Zhou C., Gao J., Zhang X., Xiao X., Wu X., Peng R. Effect of deep cryogenic treatment on the mechanical properties of ultrafine WC-Co composite. *International Journal of Refractory Metals and Hard Materials*, 2026, vol. 134, p. 107429. DOI: 10.1016/j.ijrmhm.2025.107429.

22. Gao Y., Wang Y., Chen Z. The effect of cryogenic treatment on the mechanical properties of coated cemented carbide tools. *Materials Today Communications*, 2025, vol. 42, p. 110245. DOI: 10.1016/j.mtcomm.2025.110245.

23. Chinnasamy M., Rathanasamy R., Palaniappan S.K., Pal S.K., Muthuswamy P., Korrayi R.R., Uddin M.E. Microstructural and tribological characterization of cryogenic treated WC–Co cutting bits under different holding times for rock cutting applications. *Journal of Materials Engineering and Performance*, 2024, vol. 33, pp. 4933–4950. DOI: 10.1007/s11665-023-08291-9.

Conflicts of Interest

The authors declare no conflict of interest.