Journal of Advances in Manufacturing Engineering
Web page info: https://jame.yildiz.edu.tr
DOI: 10.14744/ytu.jame.2025.00003

Original Article

Investigation of the ultrasonic effect on surface topography of WC-Co in grinding operation with different cutting variants

Tayfur YAVUZBARUT*, Emre SANDAL, Kemal Bartu AYDIN

Nedu Bağlantı Elemanları San. ve Tic. A.Ş., Norm Tooling R&D Center, İzmir, Türkiye

ARTICLE INFO

Article history
Received: 27 February 2025
Accepted: 09 May 2025

Key words:
Surface integrity, ultrasonic assisted grinding, tungsten carbide-cobalt.

ABSTRACT

This article investigates the effect of the ultrasonic oscillation and tool angles during grinding on the surface integrity of the tungsten carbide-cobalt (WC-Co). In that sense, the WC-25Co workpiece was machined through an ultrasonic-assisted grinding (UAG) process under varying ultrasonic modes and tool angles. During the UAG process, the ultrasonic mode was activated as a 40 kHz-continuous oscillation in each operational condition while the remaining grinding parameters were kept constant. The surface integrity of the machined workpiece was investigated in terms of morphology and roughness characteristics to reveal the process-structure-property relationship. Optical Microscopy (OM) and Scanning Electron Microscopy (SEM) were used to characterize the workpiece morphologically. Additionally, surface roughness indicators (Ra, Rz, and Rmax) were measured by stylus profilometer. Results revealed that the ultrasonic oscillation adversely affected the surface in the drilling operation in which Ra increased by two-fold. However, the ultrasonic oscillation yielded a better surface under the different tool angles during surface grinding. Accordingly, Ra values in the condition of surface grinding with a 45° tool angle were dropped with the ultrasonic assistance from 0.86 μm to 0.33 μm while from 0.39 μm to 0.29 μm in the condition of oscillation perpendicular to the tool path.

Cite this article as: Yavuzbarut, T., Sandal, E., & Aydın K. B. (2025). Investigation of the ultrasonic effect on surface topography of WC-Co in grinding operation with different cutting variants. *J Adv Manuf Eng*, 6(1), 14–21.

INTRODUCTION

Grinding is a critical machining operation that is used to achieve precise forms and tolerances in parts through high-speed rotating wheels or specialized abrasive tools [1]. This process plays a vital role in manufacturing by providing the ability to achieve the desired surface quality, particularly for hard and brittle materials. The effectiveness of the grinding operation is directly linked to the surface finish of the machined part, making it essential for finishing operations. While effective, traditional grinding methods have limitations, including low material removal rates, extended processing times, and high wear rates for cutting tools. These drawbacks have spurred interest in developing more efficient techniques [2–5].

One promising approach for hard-to-shape materials is ultrasonic-assisted grinding (UAG), also known as rotary ultrasonic machining (RUM), which integrates ultrasonic vibrations into the conventional grinding process [6, 7]. The concept of UAG emerged from research conducted in 1961, where it was discovered that introducing vibrations could enhance the grinding process [8]. The ultrasonic vibration leverages the material removal with brittle fractures, originating from the indentation of a vibrating tool

***Corresponding author.**
*E-mail address: tayfur.yavuzbarut@normtooling.com

with abrasive particles to the workpiece, while its rotation enables an improved surface finish with a high removal rate [6, 7, 9]. Additionally, when ultrasonic oscillation is activated, excessive heating in the cutting zones of the workpiece and tool is hindered since they do not have constant contact during operation. These vibrations help to break up the abrasive particles and enhance material removal, leading to a more effective grinding operation.

Early studies on UAG demonstrated several advantages over conventional grinding methods. Key benefits included increased material removal rates (MRR), reduced processing temperatures, and a significant decrease in cutting forces. For instance, Feucht et al. [10] found that ultrasonic oscillation reduces the cutting force by up to 30% compared to traditional grinding methods. This reduction in force not only improves the efficiency of the process but also extends the life of the grinding tools. Additionally, the introduction of ultrasonic vibrations helps to minimize surface burns and improve the overall surface finish of the hard and brittle workpiece [8].

The literature reveals a range of studies that have explored the impact of ultrasonic processing on traditional grinding techniques. Research has focused on comparing stationary ultrasonic machining with rotational ultrasonic machining, examining how these methods affect surface quality and material removal. Wdowik et al. [11] compared the surface roughness of ZrO_2 specimens processed using conventional grinding and UAG. While differences in surface morphology were observed, the roughness values were not significantly affected, suggesting that other factors, such as the grain size of the grinding tool, might influence these results. In another study, Gong et al. [12] investigated the effects of ultrasonic processing on surface milling, particularly with optical K9 glass. The study found that ultrasonic mode reduced tool wear during lateral processing and improved overall process performance, especially at lower feed rates and increased processing depths. This suggests that ultrasonic assistance can enhance the efficiency of machining hard and brittle materials. Further research by Kuruc et al. [13] focused on polycrystalline cubic boron nitride, aiming to achieve minimal surface roughness while maintaining high precision in machining. The study utilized RUM but did not compare the results with non-ultrasonic processing of the same material. Similarly, Kataria et al. [14] conducted experiments with ultrasonic machining on tungsten carbide-cobalt (WC-Co) materials, evaluating tool wear and MRR. The study revealed that increasing cobalt content in WC-Co materials led to a decrease in MRR, attributed to the linear relationship between cobalt ratio and fracture toughness. Feng et al. [15] demonstrated that UAG significantly reduces grinding forces and improves surface quality in WC-Co workpieces for blind holes and internal threads, with optimal results at a 4 μm vibration amplitude. Additionally, the method extends tool life and enhances thread accuracy by minimizing abrasive wear and maintaining dimensional consistency. Uhlmann et al. [16] studied the drilling of cemented carbide with ultrasonic assistance by investigating parameters to increase the process productivity. They showed a decrease in process force by ultrasonic assistance, which is attributed to a discontinuous cutting and crack induction. Qi et al. [17] found that ultrasonic assistance improved passivation efficiency by around 26% and decreased milling force by half for the abrasive finishing of WC-8Co. Huang et al. [18] conducted an ultrasonic-assisted mill-grinding of tungsten carbide under different spindle speeds and vibration amplitudes. They revealed that ultrasonic assistance decreased the form error and contour line roughness of the workpiece by around 42.23%. Li et al. [19] performed UAG to drill ceramic matrix composites, which reported the cutting force was decreased by around 50% with a 10% increased MRR. Abdo et al. [20] studied the effect of machining and ultrasonic parameters on the surface roughness of the zirconia ceramic through Taguchi design. They proposed a model for surface roughness (Ra) value as a function of spindle speed, feed rate, ultrasonic power, frequency, and cutting depth by using Analysis of Variance (ANOVA). Researchers found the optimum Ra value of 0.43 μm when spindle speed, feed rate, ultrasonic power, frequency, and cutting depth are 6000 rpm, 50 mm/min, 23 kHz, and 0.025 mm, respectively.

Literature studies signify the importance of the UAG application on hard and brittle materials by focusing on individual or combined effects of ultrasonic and machining parameters on tool wear and/or process efficiency. However, there is still a gap in the literature on the UAG of the WC-Co workpiece in terms of surface integrity. In addition to the ultrasonic assistance in the grinding of WC-Co, abrasive tool condition plays a critical role in chip formation mechanisms, tool wear, and energy consumption during the process. The combined influence of ultrasonic vibration and tool angles offers valuable insights for optimizing process parameters and extending tool life in high-precision applications. Therefore, the comparison was performed through the ultrasonic assistance effect on the surface roughness of the WC-Co workpiece in grinding with different tool angles. This study aims to address the relevant gaps by investigating the effects of tool position and ultrasonic assistance on the surface quality of WC-Co material. The machined workpiece was examined through morphology and roughness to elaborate surface integrity dependence on the UAG machining conditions.

MATERIALS AND METHODS

The work was carried out on a workpiece made of WC-Co (25 wt.% of cobalt and WC grain size < 5μm). Figure 1 shows the machine (Ultrasonic 20 linear, DMG Mori Sauer) that grinding operations were performed with a spindle used on the device (MFW-1224/42 VC HSK-E32, Fischer Spindle Group A.G). Figure 1b also displays the rotation and ultrasonic oscillation directions of the spindle. Since the grinding operation is performed using the same CAM, the tool path, feed rate, and spindle speed are kept constant for each cutting variant.

The ultrasonic mode was exclusively activated and deactivated during the operation. The ultrasonic mode activation corresponds to 40 kHz-continuous ultrason-

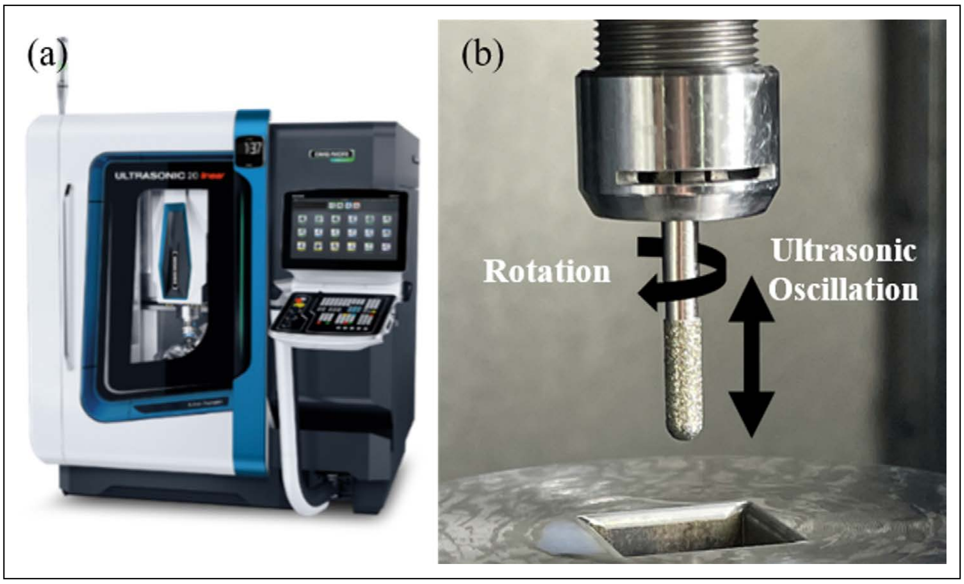

Figure 1. **(a)** Machine in which grinding was performed and **(b)** representative directions of the rotation and ultrasonic oscillation of the spindle.

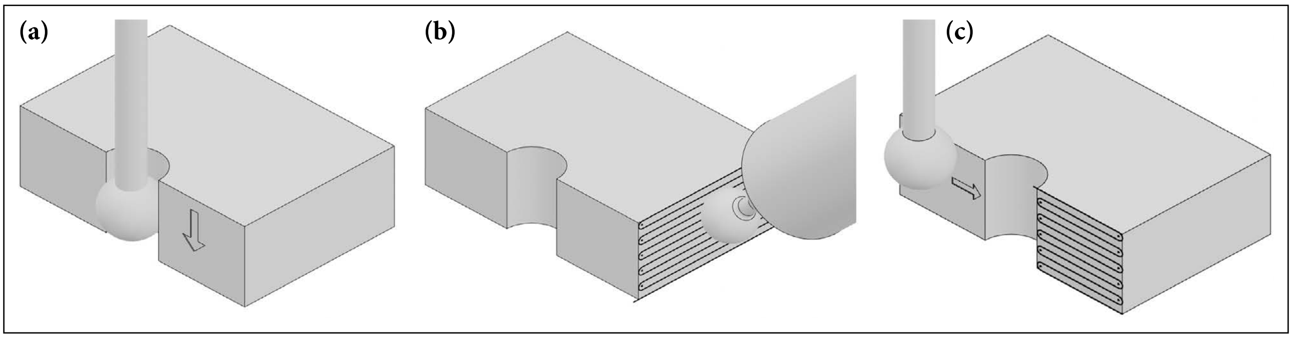

Figure 2. Schematic representation of operations by illustrating 3D models of the tool and workpiece. Accordingly, Operations **a, b,** and **c** represents the cases of drilling, surface grinding with 45° tool angle, and a lateral surface grinding, respectively.

ic oscillation during the operation. Each procedure was performed using a newly unsealed cutting tool under a boron oil environment. Each grinding operation was illustrated schematically in Figure 2.

Table 1 displays operations established during grinding. Operation A is a drilling process that includes the tool positioned perpendicular to the workpiece. The parameters used during the drilling operation are 400mm/min feed rate and 6000 RPM. In Operation B, the process was carried out at 12000 RPM and 45° tool angle with a 600 mm/min feed rate. In operation C, machining was performed on the lateral surface with 6000 RPM and 600 mm/min feed rate.

Ø6 sphere d126 (Effgen) cutting tool was used in all operations. The code 126 in the tool corresponds to the abrasive grain size in the tool. M12 code has been added and removed from the NC code to turn the ultrasonic mode on and off on the device. After processing the parts, surface images were taken with optical microscopy (ZEISS Smartzoom 5). In addition, scanning electron microscopy (SEM, Carl Zeiss 300VP) was used to elaborate the machined surface topography of the workpiece. Surface roughness measurements were conducted using a MarSurf LD 130 device and BFWA 10-45-2 13440 probe. The roughness measurements were performed according to the DIN EN ISO 4288 standard. Figure 3 shows the probe direction during surface roughness measurement.

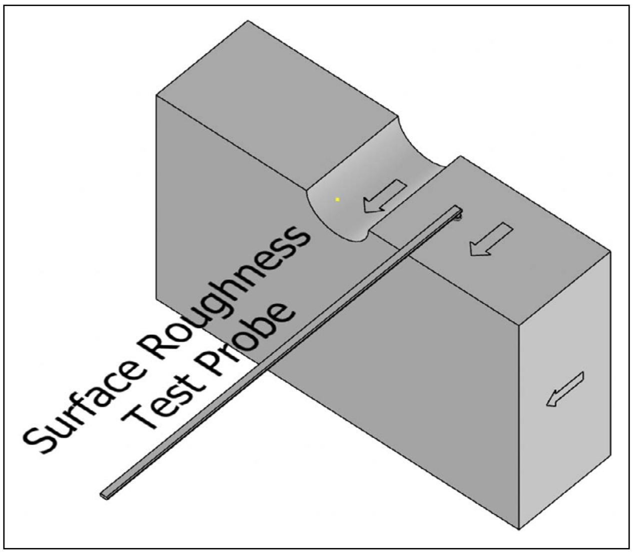

Figure 3. Probe direction during surface roughness measurement.

Table 1. The parameters of the UAG

Operation	**A**	**B**	**C**
Ultrasonic mode	**Off/On**	**Off/On**	**Off/On**
Spindle speed (rpm)	6000/6000	12000/12000	6000/6000
Feed rate (mm/min)	400/400	600/600	600/600
Machine model		Linear ultrasonic 20 DMG MORI	
Gripper		ER11 collet ultrasonic	
Coolant		Boron oil	
Grinding tool		Effgen d126 ball	

UAG: Ultrasonic-assisted grinding.

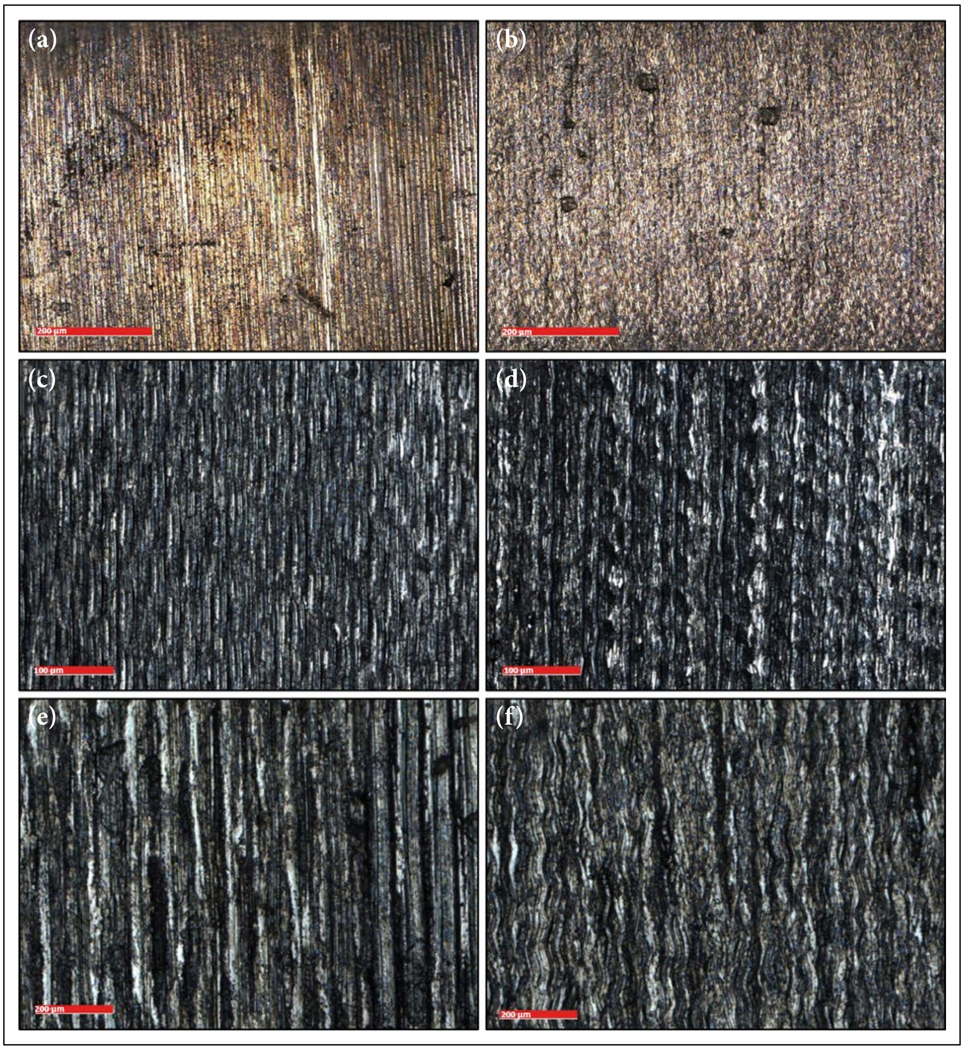

Figure 4. The images were formed as a result of Operation A in **(a, b)** with x452 magnification, Operation B in **(c, d)** with x610 magnification, and Operation C **(e, f)** with x1000 magnification. Processed with **(a, c, e)** non-ultrasonic machining and **(b, d, f)** ultrasonic machining.

RESULTS AND DISCUSSION

The workpiece surfaces obtained from the study were visualized with the help of an optical microscope (OM). OM images taken from vertical drilling (A operation), 45-degree machining (B operation), and lateral surface machining (C operation) are shown in Figure 4.

Figure 5 displays SEM images of the ultrasonic and non-ultrasonic machining of vertical drilling, 45-degree machining, and vertical milling surfaces, respectively.

OM and SEM images indicate that tool marks observed in a normal machining process appear wavy, which is thought to contribute to increased surface roughness due to the ultrasonic effect. In Operation B, where the most significant effect is observed, the inclined position of the abrasive tool during ultrasonic oscillation is believed to exert both perpendicular and horizontal influences on

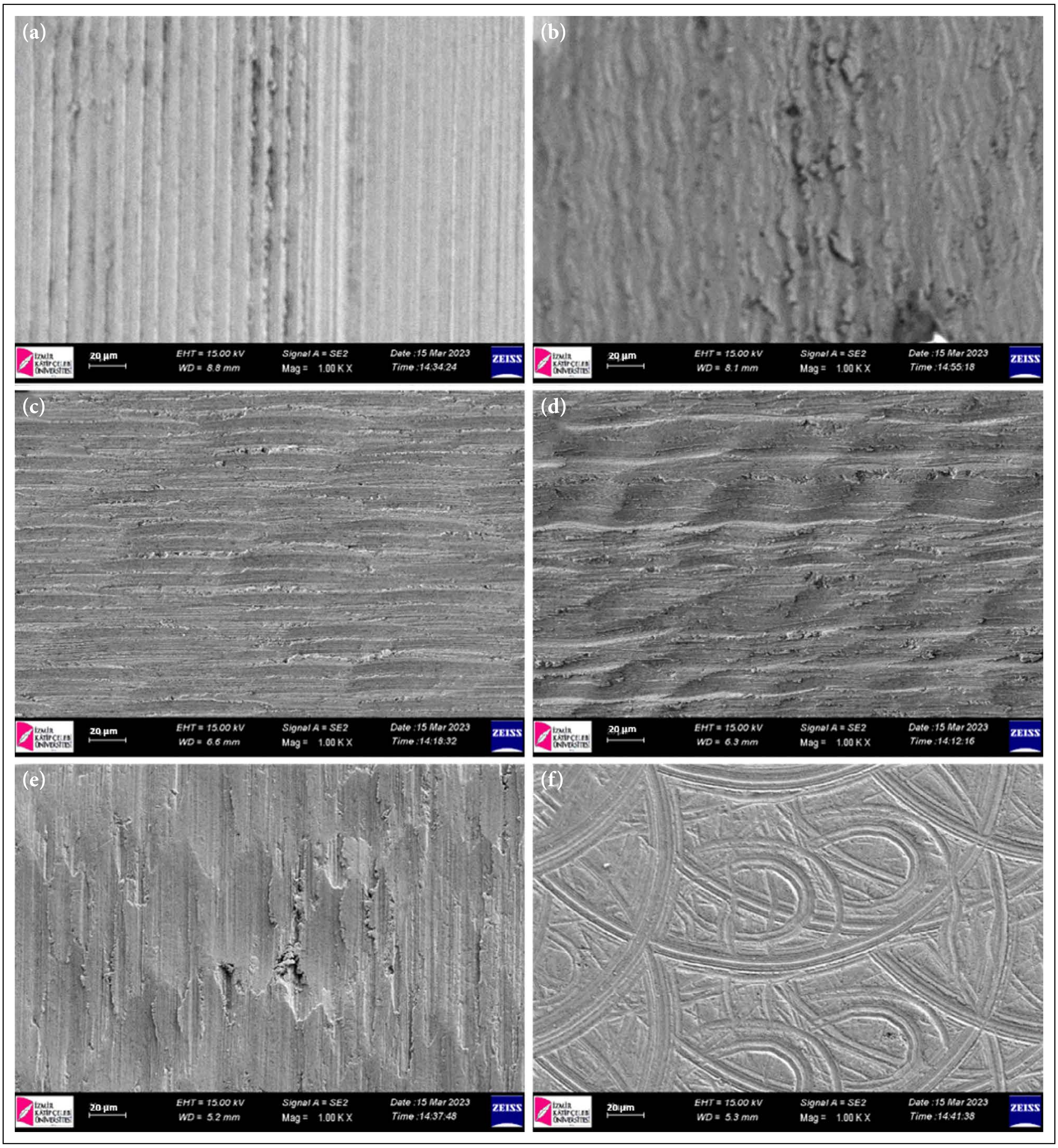

Figure 5. SEM images of workpieces' machined surface under the conditions of Operation A **(a, b)**, Operation B **(c, d)**, and Operation C **(e, f)**. For each operation, the left-hand figures show surfaces grinded without ultrasonic oscillation while the right-hand figures represent surfaces grinded with ultrasonic mode.

SEM: Scanning electron microscopy.

the surface, resulting in the maximum effect. The results suggest that the tool angle and machining direction directly impact surface roughness values. In Operation C, the occurrence of circular patterns is attributed to the result of oscillations in the Z-axis while the tool traverses along the X-axis, leading to overlapping circular paths. Considering the material removal mechanism from the surface morphology, the direction of ultrasonic oscillation significantly affects the surface condition.

The surface roughness results obtained from the workpieces' surface and their visual comparison are given in Table 2 and Figure 6, respectively. In drilling operations (Operation A), ultrasonic oscillation adversely affected surface integrity conditions, which resulted in an increase of around 2 times in the mean surface roughness value (Ra). Mechanistically, it was attributed that chips formed during grinding disrupted the operation by running into the grinding zone between the tool and the workpiece. Under

Table 2. Surface roughness measurement results of workpieces machined under different operations

	Operation A		Operation B		Operation C	
	Non-ultrasonic	**Ultrasonic**	**Non-ultrasonic**	**Ultrasonic**	**Non-ultrasonic**	**Ultrasonic**
Ra (μm)	0.16	0.32	0.86	0.33	0.39	0.29
Rz (μm)	1.19	2.06	3.90	2.15	2.14	1.75
Rmax (μm)	1.66	2.63	4.16	2.65	2.82	2.09

the condition of Operation B, the ultrasonic effect diminished the Ra by around 62%, which is attributed to the drop in both tangential and normal grinding forces compared to conventional grinding, which enhances the machining efficiency and reduces tool wear [21, 22]. Moreover, Operation C's condition yielded a decrease in roughness of about 26%. The results indicate that UAG improved surface roughness in all cases except for Operation A. The impact of ultrasonic treatment is the most prominent in Operation B.

CONCLUSION

This study dealt with the ultrasonic oscillation effect on WC-Co subjected to UAG operation with different tool angles. The different cutting variants' effects were elaborated through morphology and surface integrity to elaborate process-structure-performance linkage. Results revealed that the tool angle and ultrasonic oscillation play a crucial role in grinding the WC-Co workpiece. Accordingly, it has been observed that the parameters considered affects the material removal, which directly related with the workpiece's surface integrity. The obtained results can be summarized as follows:

- The drilling process in Operation A yielded around two-fold rough surface of the workpiece from 0.16 μm to 0.32 μm with ultrasonic oscillation. It is concluded that the same ultrasonic oscillation and tool path direction leads to an inverse effect on the surface integrity. The significant increment in Ra value was attributed to the chip evacuated that disrupted the operation by running into the grinding zone between the tool and the workpiece.
- Operation B corresponded to a surface grinding operation with a 45° tool angle, exhibiting both vertical and horizontal vibration effects. It has resulted in a significant drop in the Ra value of the workpiece from 0.86 μm to 0.33 μm with the aid of ultrasonic oscillation. The observed result was attributed to that the UAG significantly reduces both tangential and normal grinding forces, which enhances the machining efficiency and reduces tool wear.
- In Operation C, a lateral surface grinding was performed where the tool path is perpendicular to the ultrasonic oscillation. Since the chip evacuation path is not along with the tool path direction, an improvement was obtained in terms of surface integrity as the Ra value decreased from 0.39 μm to 0.29 μm with the ultrasonic assistance.

Even if the ultrasonic assistance is beneficial in machining hard and brittle materials, the overall findings revealed that different tool positioning led to distinct surface characteristics with the ultrasonic contribution. Therefore, the combined effect of both parameters should be considered during process optimization for an effective process. Furthermore, it is envisaged that this study's outcomes would guide further detailed investigations on the ultrasonic-assisted machining of hard-to-shape materials. In that sense, future work needs to investigate ultrasonic-assisted machining operations with different tool angles, different ultrasonic frequencies, and tool wear.

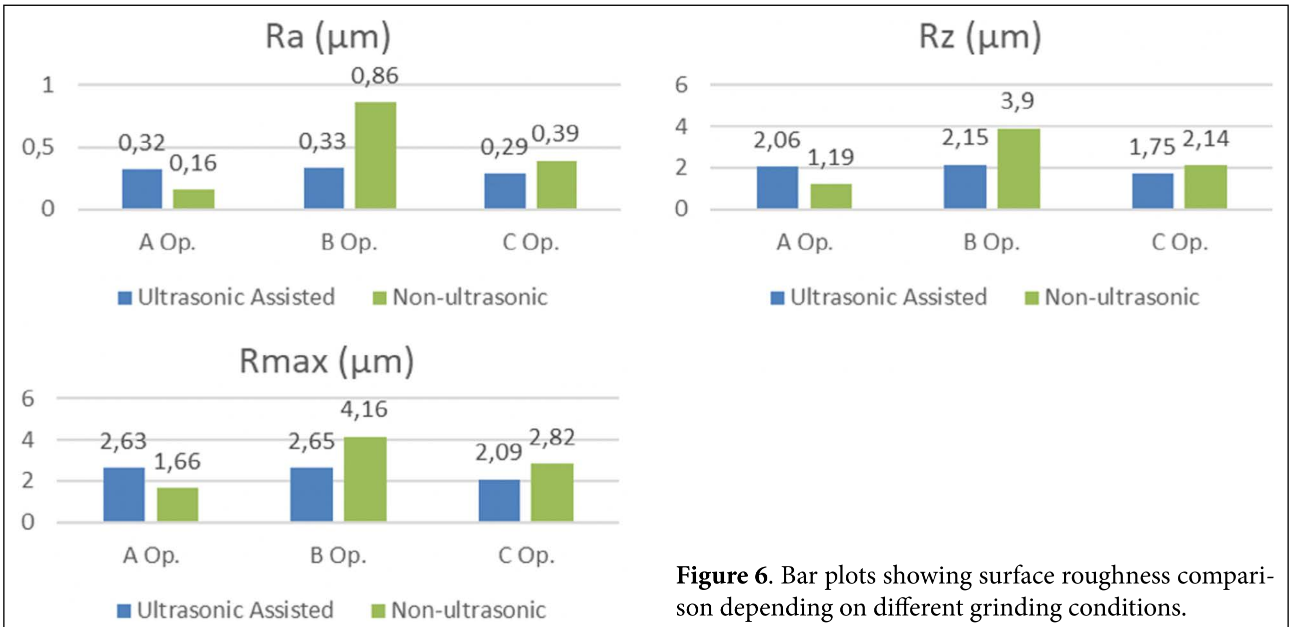

Figure 6. Bar plots showing surface roughness comparison depending on different grinding conditions.

Acknowledgements

The authors are grateful to Norm Holding for their support and encouragement in conducting this study.

Data Availability Statement

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Author's Contributions

Tayfur Yavuzbarut: Conception, Design, Supervision, Materials, Data Collection and Processing, Analysis and Interpretation, Writing, Literature Review.

Emre Sandal: Conception, Design, Materials, Data Collection and Processing, Analysis and Interpretation, Writing, Literature Review.

Kemal Bartu Aydın: Design, Supervision, Data Collection and Processing, Writing (review/editing), Critical Review.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Use of AI for Writing Assistance

Not declared.

Ethics

There are no ethical issues with the publication of this manuscript.

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