Journal of Machine Engineering, 2025, Vol. 25
ISSN 1895-7595 (Print) ISSN 2391-8071 (Online)

Received*: 30 April 2025* / Accepted: *26 May 2025* / Published online: *05 June 2025*

machining, turning,
cutting tool, cutting edge

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A COMPARATIVE STUDY OF TOOL WEAR FOR NIOBIUM CARBIDE AND TUNGSTEN CARBIDE-BASED CUTTING MATERIALS IN DRY CYLINDRICAL TURNING

Using niobium carbide (NbC) for cutting materials is a promising alternative to tungsten carbide (WC) based cutting materials for metal machining due to the inherent material properties of NbC. These include increased hot hardness and reduced chemical wear compared to WC. This study examines the application behaviour at varying cutting speeds of the cutting material composition NbC-12Ni4Mo4VC produced on a laboratory scale as well as an industrial reference cutting material based on the tungsten carbide WC-6Co. A series of measurements and analyses are conducted during the machining tests in order to evaluate the tool life, the growth of the flank wear, the cutting force and the achieved roughness of the machined surface. For NbC-12Ni4Mo4VC an increase in cutting speed correlates with an increase in tool life. As for higher cutting speeds a superior tool life of NbC-12Ni4Mo4VC is achieved compared to the industrial reference cutting tool material WC-6Co.

1. INTRODUCTION

In the present era, tungsten carbide (WC) based cutting materials dominate in industrial machining with geometrically defined cutting edges. The WC compound, first patented in 1914, has enabled a considerable increase in applicable cutting speeds v_c and longer tool life T_c due to the higher wear resistance compared to high speed steel. WC tools are considered state of the art in comparison to other cutting materials and are subject to ongoing development. A utilisation of tool coatings on WC tools has led to an additional enhancement in performance, specifically in terms of wear resistance during machining [1, 2]. Over 40% of global demand for tungsten is allocated to processing of metals, wood, stone and plastics [3]. Considering the high global demand, it is imperative to identify strategies that will reduce the consumption of tungsten. One potential solution is recycling. In the field of cutting material inserts, the recycling rate is already at an average of 55% [4]. However, as large amounts of energy are required for the recycling processes, it is vital to use tungsten as efficient as possible.

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https://doi.org/10.36897/jme/205590

Niobium carbide (NbC) has currently been utilized as a grain growth inhibitor in the production of hard metals [5]. It also possesses properties that allow cutting tool applications [6–11]. A selection of beneficial properties of NbC in comparison to WC are summarized in Table 1. The density ρ of NbC, which is lower by approximately 50% compared to WC, shows beneficial when applying NbC substrates as rotating tool material. Due to the dynamic process of machining such as milling, reduced centrifugal forces enable increased rotational speeds of the tool while maintaining a subcritical range of tool dynamics. Also, its reduced thermal conductivity λ minimizes heat accumulation at the cutting edge, thereby decreasing thermally induced wear. As stated by KLOCKE [12], using the example of cermets, a reduced thermal conductivity λ also increases the temperature gradient within the cutting material. This leads in combination with increased linear thermal expansion α to higher tensile and compressive stresses in the cutting material. Consequently, NbC potentially exhibits enhanced sensitivity to temperature fluctuations due to its reduced thermal conductivity λ and increased linear thermal expansion α when compared to WC. WC exhibits higher hardness than NbC at room temperature. NbC however has been demonstrated to exceed WC in terms of Vickers hardness HV5 above $T = 700°C$, as reported by WOYDT et al. [13]. Additionally, a higher melting temperature T_m of NbC contributes to improved resistance to plastic deformation at elevated cutting temperatures.

Table 1. Comparison of material properties at room temperature of WC and NbC [13]

Property	Unit	WC	NbC
Density ρ	g/cm³	15.63	7.81
Thermal conductivity λ	W/mK	84	14
Linear thermal expansion α	ppm/K	5.5	6.6
Micro-hardness	GPa	24–28	17–22
Melting temperature T_m	°C	2870	3520

Furthermore, a lower solubility of NbC in solid metals, including iron, cobalt, nickel, and chromium, results in less chemical wear on the cutting surface of the tool compared to WC [13]. The lower tendency to crater wear of NbC tools has been confirmed in machining tests [8–10]. These favourable properties position NbC as a promising alternative to WC as a cutting material base. In order to evaluate the potential for substituting the cutting material WC with NbC, machining tests are conducted and presented in this paper. In this case, a NbC based cutting material is used and compared to an industrial WC based reference cutting material. In previous machining tests using NbC as a cutting material, the impact of the cutting edge preparation on the application behaviour has been analysed [8]. Brushing the cutting edge has led to reproducible material properties, but cutting edge stability due to the laboratory scale development of NbC cutting materials have occasionally led to premature tool failure. Occasional cutting edge fractures due to insufficient stability have also been documented in other machining trials by UHLMANN et al. [8, 9, 11]. GENGA et al. [7] have previously utilized NbC tools with chamfered cutting edges in their milling tests, achieving satisfactory results. Chamfering the cutting edges has been demonstrated to exert a beneficial influence on the application behaviour of other cutting materials as well [12]. Additionally, BOUZAKIS et al. [14] has identified that chamfering reduces the loads applied to the cutting edge during machining. Moreover, CHEN et al. [15] has demonstrated that chamfered cutting tools reduce tensile principal stresses during the hard turning of AISI H13 compared to rounded edges. Specifically, the use of chamfered edges resulted in a 25% reduction in tensile stresses which in turn enhances tool lifetime T_{VB}. These findings highlight the benefits of chamfering the cutting edges in machining processes, as it has the potential to enhances the tool life T_c. This is of particular importance for cutting materials such as NbC, which are prone to premature tool failure due to the due to the lack of reproducible quality of the manufacturing process. As already mentioned, NbC shows beneficial properties for the use in milling applications. However, indexable inserts are used in this study in order to investigate the tool and workpiece interaction during simplified application conditions when using longitudinal cylindrical turning as machining operation. Thus, a basic comparison of the cutting material properties with WC is ensured. This approach allows the comparison of the cutting materials at constant cutting conditions with regard to the constant chip thickness h and a continuous cut. The results of this investigation serve as a starting point for future work with rotational tools. During the machining tests, the tool life T_c, the cutting forces F_c and the arithmetic mean roughness Ra generated are measured and analysed.

2. EXPERIMENTS

2. 1. SELECTION OF CUTTING TOOLS

The NbC tools used in the presented machining tests are of the composition NbC-12Ni4Mo4VC and have been fabricated by KATHOLIEKE UNIVERSITEIT LEUVEN, Leuven, Belgium. This cutting material features a nickel (Ni) binder with a volume percent of $\varphi = 12$ vol. % and vanadium carbide (VC) as a secondary carbide. For comparison, commercially available WC-6Co tools of grade H13A, containing $\varphi = 6$ vol. % cobalt (Co) binder, produced by SANDVIK COROMANT, Sandviken, Sweden, have been selected as an industrial reference. Mechanical properties of both cutting materials are listed in Table 2.

Table 2. Comparison of mechanical properties of WC-6Co and NbC-12Ni4Mo4VC [10, 16]

Property	Unit	WC-6Co	NbC-12Ni4Mo4VC
Vickers hardness HV 30	N/mm^2	1600	1280±5
Fracture toughness K_{IC}	MPa√m	N.A.	10.03±0.1

For the purpose of this study, the cutting material NbC-12Ni4Mo4VC has been manufactured through a pressure-less sintering process into discs with a diameter of $d = 55$ mm. The discs have been surface-ground on both sides. After that, individual square indexable insert blanks with a side length of $l_s = 13$ mm and a thickness of $t = 4.5$ mm have been cut from the discs using wire electrical discharge machining. Subsequently, tools have been ground from these blanks according to ISO Geometry SPUN120308. For the machining tests, an entering angle of $\kappa = 60°$, an orthogonal rake angle of $\gamma_0 = 5°$, and an inclination angle of $\lambda_s = 0°$ are chosen. NbC-12Ni4Mo4VC tools with two different cutting edge geometries are utilised during the machining tests. A selection of NbC-12Ni4MO4VC tools feature a rounded cutting edge, comparable to the WC-6Co tools, while another batch of NbC-12Ni4Mo4VC tools are provided with a chamfered cutting edge. In this instance the cutting edges are chamfered at an angle of $\gamma_\beta = 20°$ with a length of $l_\beta = 0.2$ mm. As previously stated, it is anticipated that chamfering will stabilise the cutting edge and eliminate premature failure.

Edge preparation has been measured using an INFINITE FOCUS SL from ALICONA IMAGING GMBH, Raaba, Austria. Here the cutting edge form factor *K*, cutting edge radius r_ε, and cutting edge surface roughness Ra_s of all tools used have been measured. Obtained results are shown in Fig. 2 where the diagrams represent the range and the mean value of the data. The *K* factor examination reveals that the *K* factor of all tools used is $K > 1$. This indicates that the cutting edge geometry is pronounced towards the rake face, see Fig. 1. Cutting edge chamfers have been ground to provide the other set of NbC-12Ni4Mo4VC tools with a more robust cutting edge geometry, see Fig. 1b.

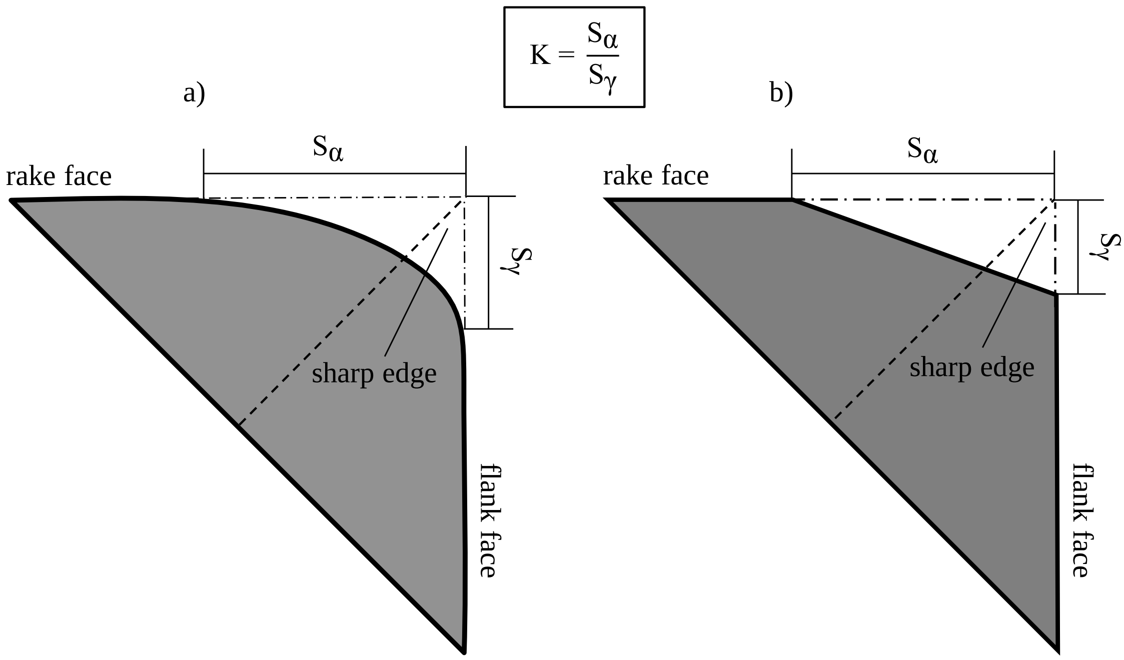

Fig. 1. Cutting edge form factor *K* according to DENKENA et al. [17]; a) rounded cutting edge geometry; b) chamfered cutting edge geometry

Sandblasting has been utilised to produce rounded NbC-12Ni4Mo4VC tools, see Fig. 1 a. This process has been successfully applied to produce rounded NbC-12Ni4Mo4VC tools with a comparable cutting edge form factor *K* and cutting edge radius r_ε to the factory rounded WC-6Co tools, see Fig. 2a and 2b. With an identical average cutting edge form factor of $K = 1.4$, the rounded NbC-12Ni4Mo4VC tools differ from the WC-6Co tools only by a slightly increased scattering. However sandblasting led to an increased cutting edge surface roughness Ra_s by approximately 119% compared to the WC-6Co tools, see Fig. 2c. Chamfered NbC-12Ni4Mo4VC tools on the other hand display an elevated cutting edge form factor of approximately $K = 2.8$ and a cutting edge roughness Ra_s comparable to WC-6Co tools. NbC-12Ni4Mo4VC tools generally exhibit a greater variation in edge preparation compared to WC-6Co tools, indicating a reduced reproducibility of the cutting edge quality.

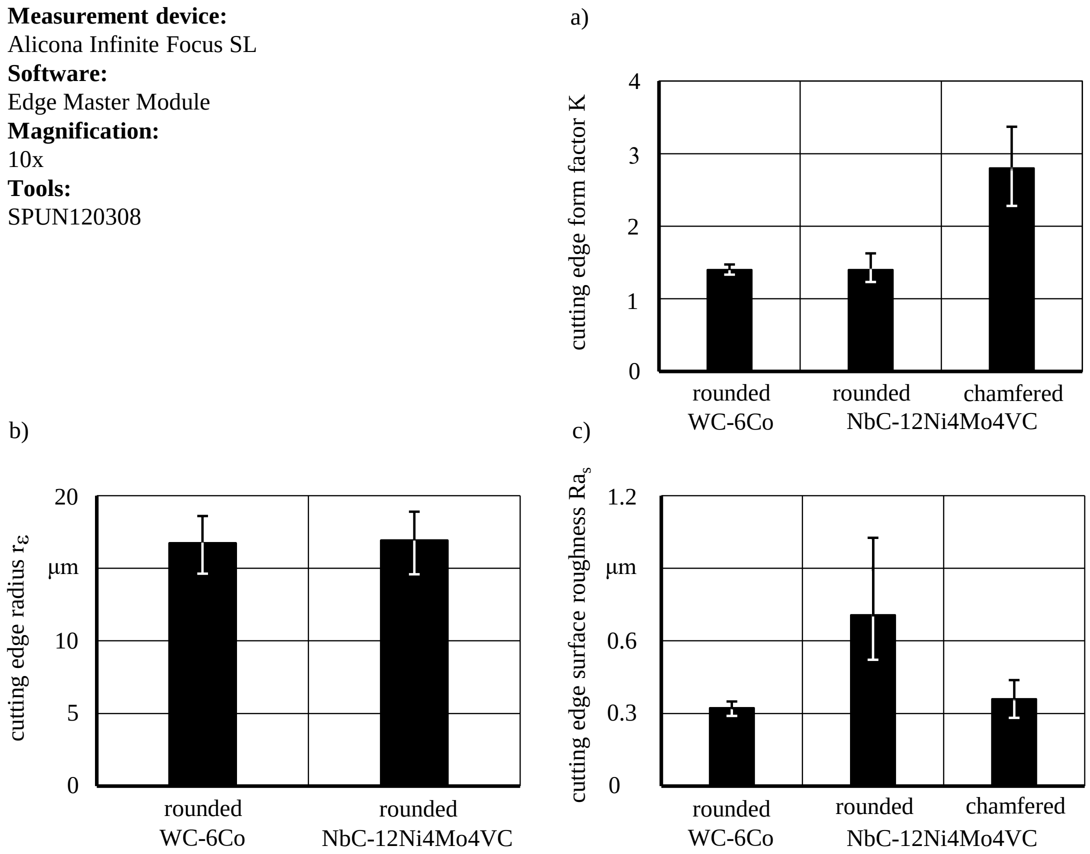

Fig. 2. Comparison of cutting edge properties; a) cutting edge form factor K; b) cutting edge radius r_ε; c) cutting edge surface roughness Ra_s

2.2. EXPERIMENTAL SETUP

To compare the performance of the WC-6Co and NbC-12Ni4Mo4VC cutting tools, longitudinal cylindrical turning test have been carried out. These have been conducted on a turning machine type VDF 180 C by OERLIKON-BOEHRINGER GMBH, Göppingen, Germany. The steel C45E has been selected as the machining material. This material is commonly used in components across general mechanical engineering [18]. A maximum wear width of VB_{Bmax} = 0.2 mm is used for quantitative evaluation of tool wear in accordance with ISO 3685 [19]. This approach provides a reliable framework for assessing tool wear. Additional relevant information on determining tool wear are summarised by GRZESIK [20]. The wear width VB_{Bmax} is evaluated using a digital light microscope, model VHX 5000, from KEYENCE CORPORATION, Osaka, Japan. Arithmetic mean roughness Ra of the machined workpiece surface is measured using the WAVELINE W5 surface measuring instrument by HOMMEL ETAMIC GMBH, Villingen Schwenningen, Germany. To monitor cutting forces F_c during the process, a dynamometer type Z13764 and a charge amplifier type LABAMP 5167A, both produced by KISTLER INSTRUMENTE AG, Winterthur, Switzerland, are employed. The cutting speeds conducted are v_c = 150 m/min, v_c = 200 m/min, and v_c = 250 m/min. For each combination of cutting speeds v_c, three machining repetitions are performed, with a fixed feed rate of f = 0.15 mm and a depth of cut of a_p = 0.5 mm.

3. RESULTS AND DISCUSSION

Following the conduction of the machining tests, the data regarding tool life T_c, surface roughness parameter *Ra* and cutting forces F_c is recorded and analysed. The ensuing results are presented in Fig. 3, where the mean values are shown and the error bars represent the minimum and maximum values of the three repetitions, when the wear criteria of VB_{Bmax} = 0.2 mm is attained. With increasing cutting speed v_c, the average tool life TVB of the WC-6Co and NbC-12Ni4Mo4VC cutting materials declines, see Fig. 3a. A similar behaviour has been previously discovered [6, 8, 10]. As shown in Fig. 3 WC-6Co tools demonstrate an average tool life of T_c = 635 s at a cutting speed of v_c = 150 m/min, which exceeds the tool life T_c of the rounded NbC-12Ni4Mo4VC tools with approximately 232%. This tool behaviour may be attributed to the lower hardness of NbC-12Ni4Mo4VC compared to WC-6Co at lower temperatures. Chamfering the NbC-12Ni4Mo4VC tools enhances the tool life T_c by approximately 75% compared to rounded NbC-12Ni4Mo4VC tools at a cutting speed of v_c = 150 m/min. It is conceivable that the application of a chamfer stabilises the cutting edge, thereby resulting in an enhanced average tool life T_c in contrast to the rounded NbC-12Ni4Mo4VC tools utilised. However, when the cutting speed is increased to v_c = 200 m/min, the rounded and chamfered NbC-12Ni4Mo4VC tools achieve an increased tool life T_c of approximately 92% and 168% compared to the WC-6Co tools. This improvement is related to the enhanced hot hardness. At a cutting speed of v_c = 250 m/min, the average tool life of the WC-6Co tools has been further reduced to approximately T_c = 40 s. While the rounded and chamfered NbC-12Ni4Mo4VC tools have shown a 183% and 388% increase in tools life T_c contrast to the WC-6Co tools. It is presumed that the cause of this phenomenon is related to the lower coefficients of friction μ of NbC in comparison to WC at higher temperatures T and higher sliding velocities v which have been discovered by WOYDT et al. [21]. Since WC-6Co tools are considered state of the art, a high degree of repeatability is expected. WC-6Co and rounded as well as chamfered NbC-12Ni4Mo4VC tools reach comparable statistical distribution in the achieved tool life T_c.

The measured cutting forces F_c are shown in Fig. 3b. An increasing cutting speed v_c leads to rising average cutting forces F_c for the WC-6Co. In contrast, the application of rounded NbC-12Ni4Mo4VC tools leads to a reduction in cutting force of approximately 18% when the cutting speed is increased from v_c = 150 m/min to v_c = 250 m/min. This behaviour is attributed to lower coefficients of friction μ at higher temperatures T and sliding velocities v, as well as the lower thermal conductivity λ of NbC compared to WC. Due to the lower thermal conductivity λ more heat is transferred to the chips and workpiece, increasing ductility and reducing cutting forces F_c. At a cutting speed of v = 250 m/min, the average cutting force F_c of the chamfered NbC-12Ni4Mo4VC tools increases only by approximately 5 % compared to the cutting force F_c measured at the lowest cutting speed of v_c = 150 m/min. This finding suggests a consistent process behaviour of the chamfered NbC-12Ni4Mo4VC tools across a wide range of cutting speeds v_c Moreover the chamfered NbC-12Ni4Mo4VC tools demonstrate higher repeatability of the average cutting forces F_c than the commercial WC-6Co and rounded NbC-12Ni4Mo4VC cutting material. However, when WC-6Co tools are utilized, an increase of the cutting speed from v_c = 150 m/min to v_c = 250 m/min results in an increase of the average cutting forces by approximately 27%. WC-6Co tools generate an average cutting force F_c which is about 10% lower compared to chamfered NbC-12Ni4Mo4VC tools and about 28% lower compared to the rounded NbC-12Ni4Mo4VC tools at a cutting speed of v_c = 150 m/min. In contrast, at a cutting speed of v_c = 250 m/min the average cutting force F_c of the WC-6Co tools is approximately 7% higher compared to the rounded NbC-12Ni4Mo4VC tools. This effect can be explained by the aforementioned findings of WOYDT ET AL. [21], which show that NbC has a lower friction coefficient μ at higher sliding velocities v. The effect of chamfering NbC-12Ni4Mo4VC cutting tools on the resulting cutting force F_c is subject to current investigations.

Figure 3c displays the arithmetic mean roughness *Ra* of the machined workpiece surface. The graphs show an decrease in the average arithmetic roughness *Ra* at higher cutting speeds v_c for the WC-6Co and rounded NbC-12Ni4Mo4VC tools. Whereas an increase in the average arithmetic roughness *Ra* at higher cutting speeds v_c, is followed by a decrease for the chamfered NbC-12Ni4Mo4VC tools. At cutting speeds of v_c = 150 m/min the WC-6Co and chamfered NbC-12Ni4Mo4VC tools achieve comparable arithmetic mean roughness *Ra*. At cutting speeds of v_c = 150 m/min and v_c = 200 m/min, the arithmetic mean roughness *Ra* achieved by the WC-6Co and rounded NbC-12Ni4Mo4VC tools remain virtually unchanged for the respective cutting material.

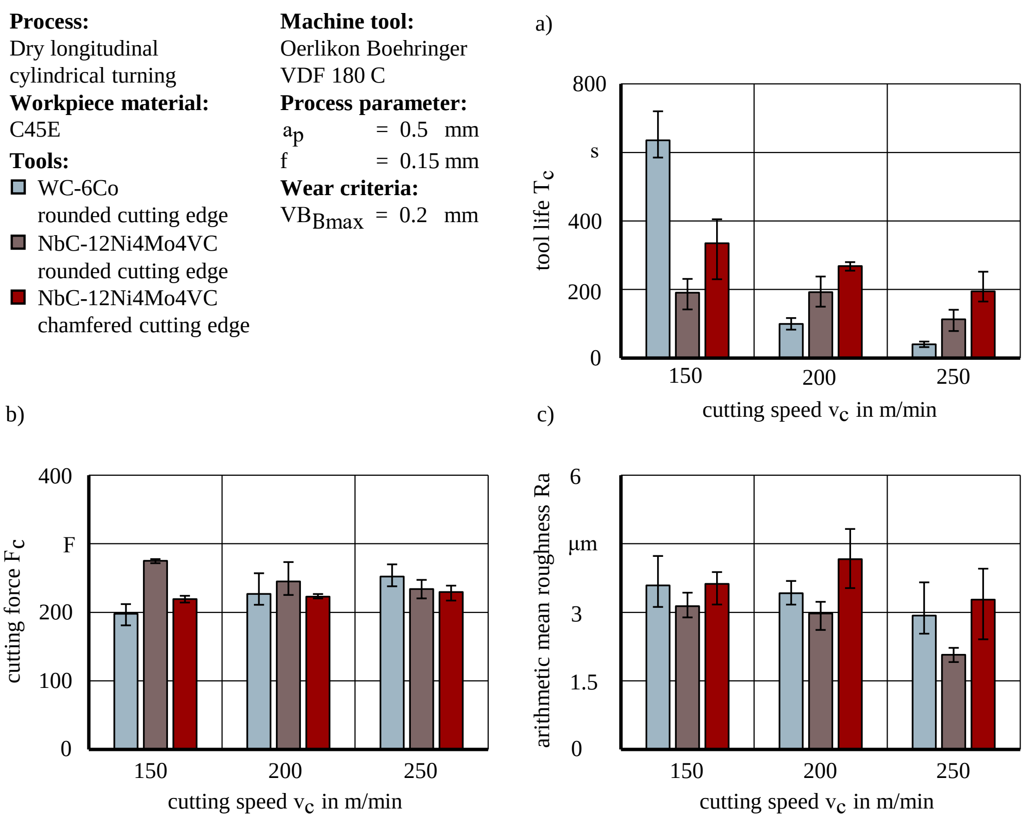

Fig. 3. Results of the machining tests; a) tool life T_c; b) cutting force F_c; c) arithmetic mean roughness *Ra*

At all investigated cutting speeds v_c, the rounded NbC-12Ni4Mo4VC tools produce lower arithmetic mean roughness *Ra* being approximately 29% lower at a cutting speed of v_c = 250 m/min compared to WC-6Co tools. Chamfered NbC-12Ni4Mo4VC tools demonstrate a higher variation of the arithmetic mean roughness *Ra* at higher cutting speeds v_c opposed to the rounded NbC-12Ni4Mo4VC and WC-6Co tools. A similar behaviour has been detected by ÖZEL et al. [22] using cubic boron nitride (CBN) tools. The presence of a cutting edge chamfer on a machining material of comparable hardness has lead to an increased arithmetic mean roughness *Ra* compared to a cutting edge without such a feature. The effect of NbC-12Ni4Mo4VC cutting material on the resulting arithmetic mean roughness *Ra* is subject to current investigations.

Figure 4 shows exemplary chosen tools which are used in the machining tests. The tools depicted here have a comparable wear width of around VB_{Bmax} = 0.2 mm. However, these tools exhibit different wear mechanisms resulting into varying wear pattern. Significant abrasive wear is present on the rake face of the WC-6Co tools. At higher cutting speeds v_c, this wear mechanism results in developing crater wear. This type of wear is caused by the high solubility of WC in steels, which is particularly noticeable at high temperatures *T* due to increasing cutting speed v_c. Abrasive wear on the rake face of the WC-6Co tool is elevated in comparison to the rounded and chamfered NbC-12Ni4Mo4VC tools. It is presumed that the cause of this circumstance is related to the lower coefficients of friction μ of NbC at higher temperatures *T* and higher sliding velocities v which have been discovered by WOYDT et al. [21].

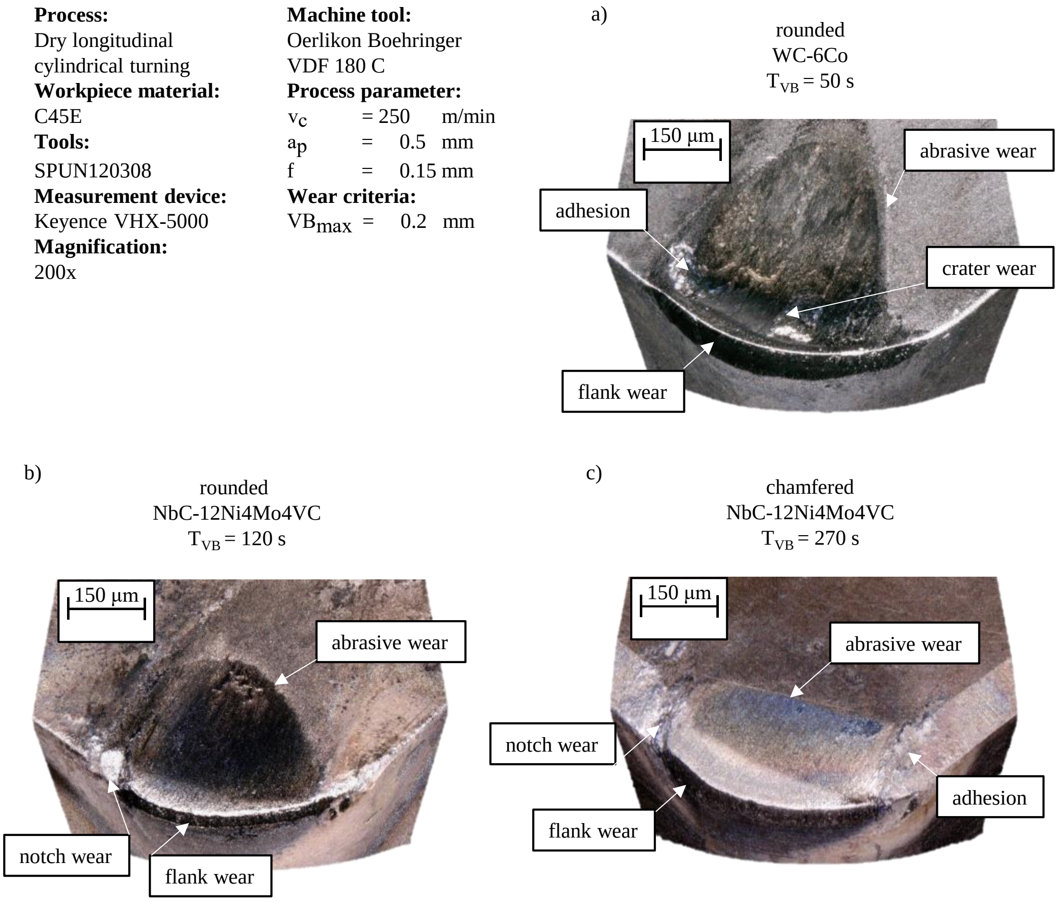

Fig. 4. Tools after reaching the wear criteria VB_{Bmax} = 0.2 mm at a cutting speed of v_c = 250 m/min; a) rounded WC-6Co; b) rounded NbC-12Ni4Mo4VC, c) chamfered NbC-12Ni4Mo4VC

Whereas the chamfered NbC-12Ni4Mo4VC tool shows the least amount of abrasive wear. A chamfer deflects the chip from the rake face, thereby reducing the load on this area. However, this process also seems to result in higher temperatures *T* at the cutting edge as evidenced by the bluish discolouration in comparison to the rounded NbC-12Ni4Mo4VC tools. Adhesion of workpiece material is present on all tools. Diffusion wear in the form of crater wear and abrasive wear on the flank face are the dominant wear mechanisms of the WC-6Co tools. Unlike WC-6Co, rounded and chamfered NbC-12Ni4Mo4VC tools display notch wear. This is likely due to the lower hardness HV30 of NbC-12Ni4Mo4VC in comparison to WC-6Co which results in a reduced resistance to abrasion. Notch wear appears more pronounced on the rounded NbC-12Ni4Mo4VC tools compared to the chamfered NbC-12Ni4Mo4VC tools. This, combined with the lower tool life *T*, suggests that notch wear develops faster at higher cutting speeds v_c without a chamfer. Additionally, a discolouration beneath the secondary cutting edge of the rounded and chamfered NbC-12Ni4Mo4VC tools, extending to the main cutting edge is visible. It is presumed that the lower thermal conductivity λ of NbC compared to WC is a contributing factor. The reduced thermal conductivity λ apparently hinders the dissipation of heat into the tool which is generated during the cutting process. This results in localised temperature peaks on the cutting edge surface that presumably lead to discolouration of the NbC-12Ni4Mo4VC substrate.

Additionally the increased linear thermal expansion α may lead to an increase in tensile and compressive stresses within the cutting material. Whether this circumstance impacts the observed wear behaviour is subject to future investigations. Adhesive wear in the form of notch wear and abrasive wear on the flank face are the dominant wear mechanisms of the NbC-12Ni4Mo4VC tools.

4. SUMMARY AND CONCLUSION

This study compares the experimental NbC-12Ni4Mo4VC cutting material with the industrial reference cutting material WC-6Co in terms of performance during the machining of C45E steel. In earlier studies by UHLMANN et al. [8, 9] and KROPIDLOWSKI et al. [10] various NbC compositions have been applied as cutting material. However, premature tool failure due to insufficient cutting edge stability and presumably inadequate cutting material composition has occurred. Spontaneous tool failure appears to be eliminated in the present study by using NbC-12Ni4Mo4VC. Results indicate that NbC-12Ni4Mo4VC tools offer enhanced tool life T_c at higher cutting speeds v_c, presumably due to increased hot hardness and reduced solubility in solid metals in comparison to WC-6Co. This is particularly evident in machining tests conducted at cutting speeds of $v_c = 200$ m/min and $v_c = 250$ m/min. A substantial enhancement in tool life T_c of 183% and 388% can be attained with the rounded and chamfered NbC-12Ni4Mo4VC tools in comparison to the industrial WC-6Co cutting material for the aforementioned cutting speeds v_c. Chamfering the edges requires further investigation, as it is a more effective solution to improve tool life T_c compared to rounding the cutting edges. Subsequent studies focus on coated NbC tools, as the application of coatings has demonstrated to enhance the tool life T_c of these tools [6, 9].

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