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# Increased tool performance with niobium carbide based cutting materials in dry cylindrical turning

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## Abstract

Niobium carbide (NbC) shows promising results as an alternative cutting tool material to tungsten carbide (WC) for turning of iron-based materials. Due to its hot hardness and low solubility of binderless NbC in solid chrome, nickel, cobalt, or iron, it presents excellent properties for cutting tool applications. These advantages result in a reduced tendency to adhesive and diffusion wear, which affects cutting tool lifetime and process stability. In order to investigate a possible substitution of the conventional substrate material tungsten carbide, the BAM Federal Institute for Materials Research and Testing and the Institute for Machine Tools and Factory Management (IWF) of the Technische Universität Berlin analyze the suitability of NbC for the use as a cutting tool in turning processes. Two different straight NbC materials are included in the machining trials prepared by Katholieke Universiteit Leuven, Belgium each differing in chemical composition and mechanical properties. A cobalt (Co) bonded niobium carbide defined as NbC<sub>0.88</sub>-12Co, a nickel (Ni) bonded NbC with the specification (NbC<sub>1.0</sub>-10TiC)-6Ni7.5VC and a commercially available cermet with a niobium content of wt.-%<sub>NbC</sub> = 25 % are selected and compared to submicron grain WC-6Co tool material. Carbon steel C45E and gear steel 42CrMo4+QT are chosen as workpiece materials of different representative technological applications for dry external cylindrical turning tests. A variation of cutting speed is carried out to show the impact of higher thermomechanical load during machining. The results evaluate the cutting performance of NbC compared to WC regarding material removal  $V_w$  and crater wear KT. In contrast to WC tools NbC cutting tools show constant material removal  $V_w$  at increased cutting speed  $v_c$  combined with a higher process reliability.

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**Keywords:** Niobium carbide (NbC), tungsten carbide (WC), tool wear, cylindrical turning

## 1. Introduction

The market for hard metal tools is currently dominated by tungsten carbide (WC) cutting materials. Compared to high speed steel (HSS) tools, machining operations in industrial manufacturing processes can be performed allowing higher cutting speeds  $v_c$  as well as efficiency enhancement in the production sector. With constant tool improvement on WC dispersed in ductile cobalt binder (WC-Co) in order to optimize its diversity of application it is regarded as state of the art cutting material. Extended tool life regarding wear resistance

can additionally be achieved with the deposition of tool coating [1].

Since 80 % of raw material of tungsten is located in China, a guaranteed supply for global consumption is subject to Chinese economic policy. This worldwide dependency classifies it as a critical resource [2]. Hence, a recent effort for an alternative option can be observed focusing on NbC as a capable high-performance substitution of conventional cutting material [3,4,5].

The potential of niobium as an alternative cutting material far exceeds the typical use as a growth inhibitor in the hard metal production or as an alloying element in cermets based

on titanium carbon nitride Ti(C,N) [6]. Promising material properties of niobium carbide (NbC) combined with a contemporary volatile price development of WC increases the attention as a powerful cutting tool application, see Table 1. Besides the long term objective to establish NbC as a reliable cutting tool material, its classification for biomedical applications shows the variety for further fields of application. Also, in contrast to cobalt, it is not subject to toxicologically relevant labelings or classifications.

Table 1. Comparison of material properties between WC and NbC [7].

Property	WC	NbC	Effect
Density $\rho$ [g/cm <sup>3</sup> ]	15.63	7.78	Reduction of centrifugal forces in rotating and dynamic tools
Melting point $T_m$ [°C]	2870	3520	Less weakening of the cutting edge at high cutting temperatures
Oxide layer	WO <sub>3</sub>	Nb <sub>2</sub> O <sub>5</sub>	No sublimation of tribochemically stable Nb <sub>2</sub> O <sub>5</sub> with high melting point at $T_{m,Nb2O5} = 1522$ °C Sublimation of WO <sub>3</sub> at approx. $T_{m,WO3} \approx 700$ °C
Thermal conductivity $\lambda$ [W/m·K]	84	14	Lower heating of NbC during machining leads to reduction of thermally induced wear
Microhardness [GPa]	20 - 28	15 - 20	Higher hot hardness of NbC at elevated temperatures as of approx. $T_H \approx 900$ °C
Solubility in solid			Reduction of chemical (crater-) wear during machining of materials with alloying elements nickel, cobalt, iron
Nickel,	12	3	
Cobalt,	22	5	
Iron	7	1	
at $T = 1250$ °C [wt.-%]			

In order to resist wear mechanism such as adhesion, abrasion, tribomechanical wear and surface attrition in machining operations, tools require high hardness and toughness. Additionally, high mechanical strength as well as thermal and chemical stability is required to meet the conditions in high performance machining and ensure process stability.

Due to a lower solubility of binderless NbC in solid chrome (Cr), nickel (Ni), cobalt (Co) and iron (Fe) compared to WC, a reduced chemical wear on the rake face is expected [7]. The higher melting point of NbC with  $T_M = 3520$  °C linked with a lower solubility in alloys reduces adhesion with the workpiece during machining [8]. Further advantageous properties such as a lower wear rate caused by friction at elevated speeds and a higher hot hardness as of  $T \approx 800$  °C of substoichiometric and stoichiometric NbC substrates compared to WC-6Co have been reported [9,10]. Taking into account the conditions in machining operations based on thermomechanical loads, NbC displays the capacity as a cutting tool for a variation of steel based workpiece materials.

## 2. Cutting materials

The NbC tools used in this wear investigation are defined as NbC<sub>0.88</sub>-12Co and (NbC<sub>1.0</sub>-TiC)-6Ni7.5VC and are manufactured by KATHOLIEKE UNIVERSITEIT LEUVEN, Belgium. Commercially available WC tools with a 6 % cobalt binder manufactured by EXTRAMET AG, Plaffeien, Switzerland, denominated as WC-6Co (submicron grain), serves as the industrial reference commonly used in production. WC with a mass fraction of cobalt binder  $w_{WC} = 6$  % contains an equal volumetric fraction of binder material compared to the NbC cobalt content  $w_{NbC} = 12$  % due to the 50 % lower density  $\rho_{NbC}$ .

The cobalt bonded and substoichiometric straight NbC<sub>0.88</sub> was manufactured by Spark Plasma Sintering (SPS) with an initial primary grain size of  $d_{NbC0.88} = 150$  nm at holding temperature  $T_{HS} = 1285$  °C and sintering time of  $t_{s,SPS} = 6$  min at a pressure of  $p_{SPS} = 30$  MPa.

For the manufacturing process of the nickel bonded NbC containing titanium carbide (TiC) and vanadium carbide (VC), stoichiometric NbC<sub>1.0</sub> powder with an initial primary grain size of  $d_{NbC1.0} = 350$  nm was processed in conventional sintering (CS) at a temperature of  $t_{CS} = 1420$  °C and sintering time of  $t_{s,cs} = 60$  min at a dynamic vacuum of  $p_{CS} = 20$  Pa.

Tools composed of WC-6Co are manufactured via hot isostatic compression (HIP) under industrial conditions. The differing microstructure of each substrate is attributed to the varying sintering process, see Figure 1.

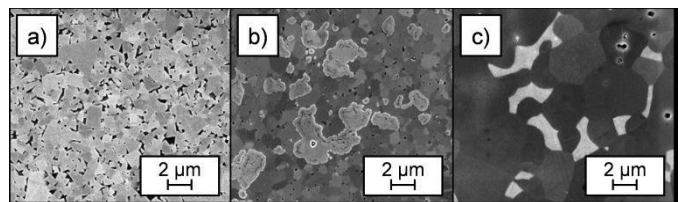


Fig. 1. Microstructure of a) WC-6Co, b) NbC<sub>0.88</sub>-12Co and c) (NbC<sub>1.0</sub>-10TiC)-6Ni7.5VC.

WC tools benefit from the elaborated industrial manufacturing process highlighted by the equal and homogenous distribution of binder and hard phase as well as small grain size. In contrast, both NbC tools lack homogeneity in distribution of substrate material and reveal coarse grains due to the laboratory scale of production.

The manufactured cutting tools offer differing mechanical properties due to the varying sintering process and the composition of the cutting materials, see Table 2.

Table 2. Mechanical properties of WC and NbC [11].

Cutting material	Vickers hardness HV 30	Fracture toughness $K_{IC}^*$ [MPa√m]	4-point bending strength $\sigma_{4pb}$ [MPa]
WC-6Co	1790	9,60	N.A.
NbC <sub>0.88</sub> -12Co	1499	5,78	1005
(NbC <sub>1.0</sub> -10TiC)- 6Ni7.5VC	1360	7,99	626

\* $K_{IC}$  = Palmqvist method with Shetty's equations

A lower hardness on both NbC substrates compared to WC substrate material cannot be linked with a lower wear resistance. Amongst others, the mechanical strength tested by 4-point bending tests needs consideration in order to compile a tribomechanical profile for a cutting material [11].

After sintering NbC<sub>0.88</sub>-12Co and WC-6Co tools are produced according to ISO geometry SPUN120408 and CNMN 120408 regarding its later application for workpiece machining. Besides SPUN120408 tools then analogous geometry CNMN090308 of (NbC<sub>1.0</sub>-10TiC)-6Ni7.5VC cutting inserts are produced due to limitations of raw material. Identical tool engagement conditions of all cutting inserts in machining trials are maintained ensuring an overall comparability.

For machining tests with SPUN120408 tools an entering angle of  $\kappa = 75^\circ$ , an orthogonal rake angle of  $\gamma_0 = 6^\circ$  and an inclination angle of  $\lambda_s = 0^\circ$  are chosen. CNMN090308 tools are implemented with an entering angle of  $\kappa = 95^\circ$ , an orthogonal rake angle of  $\gamma_0 = -6^\circ$  and an inclination angle of  $\lambda_s = -6^\circ$ .

Prototype based tool manufacturing of NbC tools caused occasional irregularities such as roughness or breakouts on the cutting edge which affected the cutting edge quality. In order to guarantee equal cutting tool features between NbC and WC tools, an additional brushing process on NbC inserts produced identical cutting edge conditions [12]. A reduction of minor breakouts and levelling of cutting edge roughness  $R_a$  as well as cutting edge radii  $r_\beta$  provided comparable inserts.

### 3. Experimental setup

The turning tests were performed on a DMG MORI AG, Bielefeld, Germany machining center CTX gamma 1250 TC. The assessment of the cutting materials was carried out via dry longitudinal cylindrical turning. According to ISO 3685 the maximum wear width  $VB_{max} = 0.2$  mm and crater wear depth KT are used for quantitative wear evaluation [13]. By interrupting the cutting process at fixed intervals of  $t_1 = 5/15/30/60$  s, the measurement of the flank wear was realized. In each case, three machining trials ( $n = 3$ ) for all combinations of cutting material, workpiece material and cutting speed  $v_c$  were performed.

### 4. Results

Machining trials with carbon steel C45E as well as hardened, quenched and tempered steel 42CrMo4+QT showed the potential of NbC as a capable cutting materials substitution of WC, see Figure 2.

Machining tests with NbC<sub>0.88</sub>-12Co offer an approximated constant material removal  $V_w$  of C45E with increasing cutting speed, establishing a continuous increase in process stability. Identical tool behavior can be attributed to (NbC<sub>1.0</sub>-10TiC)-6Ni7.5VC cutting inserts exceeding the mean material removal  $V_w$  of NbC<sub>0.88</sub>-12Co and WC-6Co tools at all cutting speed variations. In addition, the reliability of this machining operation is demonstrated at the highest cutting speed due to the achieved process reliability.

While turning 42CrMo4+QT at  $v_c = 70$  m/min, NbC<sub>0.88</sub>-12Co demonstrates a fourfold higher material remo-

val  $V_w$  compared to WC-6Co. At elevated cutting speeds of  $v_c = 100$  m/min and  $v_c = 150$  m/min, NbC<sub>0.88</sub>-12Co tools occasionally confirm the before mentioned potential even though an average decrease of material removal  $V_w$  by 20 % and subsequent 30 % respectively can be observed. Spontaneous tool failure at elevated cutting speeds  $v_c = 100$  m/min and  $v_c = 150$  m/min limits the overall process stability. (NbC<sub>1.0</sub>-TiC)-6Ni7.5VC meets the requirements as a cutting tool alternative by exceeding the material removal rate of WC at all cutting speeds  $v_c$ . The mean value of the material removal  $V_w$  increases by 60 % at  $v_c = 100$  m/min and subsequent 2.5 % at  $v_c = 150$  m/min with a simultaneous increase in process stability.

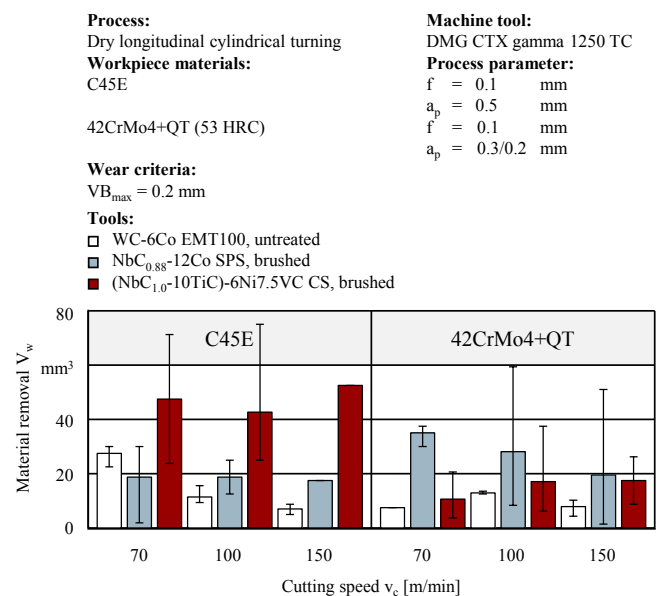


Fig. 2. Material removal  $V_w$  comparison of WC, NbC<sub>0.88</sub>-12Co and (NbC<sub>1.0</sub>-TiC)-6Ni7.5VC in machining of C45E and 42CrMo4+QT.

Apart from the evaluation of the material removal  $V_w$  the chemically induced crater wear was also quantitatively assessed, see Figure 3.

The low solubility of iron in NbC is reflected in the low crater wear measurements after machining, both C45E and 42CrMo4 Q&T. While machining C45E the crater wear for WC-6Co tools increases by a total of 82 % at higher cutting speeds  $v_c = 100$  m/min and subsequent 180 % at  $v_c = 150$  m/min. In contrast to the conventional cutting material WC, NbC grades resisted the thermo-mechanical load. Technical advantages of NbC substrates for the investigated machining operations are based on the chemically stable property combined with a low friction coefficient. Even under high performance conditions all NbC tools, varying in binder material, additives and sintering condition, attest the capability as a cutting tool for the tested workpiece materials. Compared to NbC tools, an eightfold higher measured crater wear depth KT on the cutting tools rake face of WC inserts support the applicability of this novel cutting material in machining of carbon based workpiece materials.

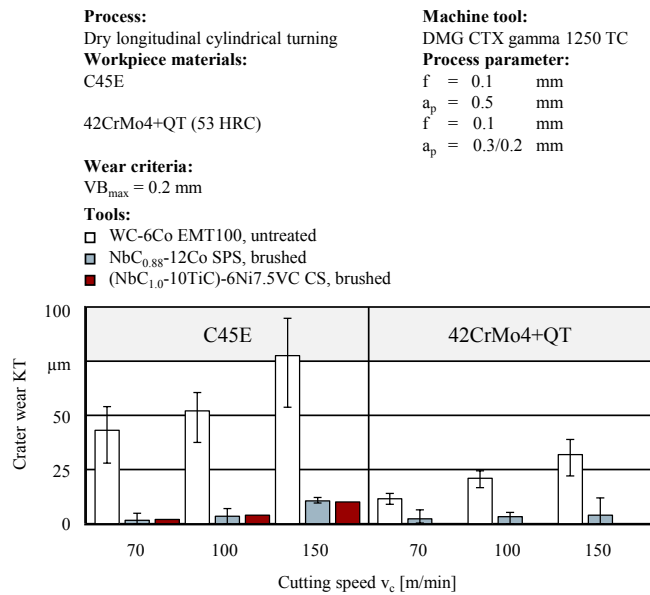


Fig. 3. Crater wear comparison of WC, NbC<sub>0.88</sub>-12Co and (NbC<sub>1.0</sub>-TiC)-6Ni7.5VC in machining of C45E and 42CrMo4+QT.

## 5. Discussion

Two NbC substrates were compared to industrially established WC-Co hard metal in dry machining of carbon steel C45E and hardened, quenched and tempered 42CrMo4+QT steel. Apart from limiting the environmental and economic impact, dry turning under semi-finishing conditions was focused to assess the application of NbC as a cutting material in dry machining condition.

The present machining results confirmed the expectations from the metallurgical and material profile of NbC. Higher material removals  $V_w$  of (NbC<sub>1.0</sub>-10TiC)-6Ni7.5VC and NbC<sub>0.88</sub>-12Co compared to WC-6Co are attested even though the hardness and toughness of the tested straight NbCs is lower. In addition to a lower solubility of NbC in alloys, high hot hardness and decreasing friction coefficients of NbC with increasing sliding speeds, advantageous properties for machining are evident. However, in machining 42CrMo4+QT, NbC<sub>0.88</sub>-12Co revealed the best tool performances. So far, the measured 4-point bending strengths according to DIN EN 843-1 of the straight NbCs were significantly lower as for WC-6Co and needs to be improved by metallurgical developments. Machining of 42CrMo4+QT generally generates high cutting forces on the tool's cutting edge with lab scale NbC substrates prone to suffer spontaneous tool failures due to the lower mechanical strength of the material. The experimental straight NbC inserts display varying properties compared to the elaborated and industrially manufactured WC grades.

Furthermore, pores are present in the (NbC<sub>1.0</sub>-10TiC)-6Ni7.5VC substrate due to the reduced binder content to increase the hardness. In addition, the grain growth in straight NbCs during conventional sintering must be limited. By adding secondary carbides and using nickel-molybdenum binders the functional profile can be further optimized [14].

## 6. Conclusions

NbC-based tools demonstrated great potential in turning of iron-based work pieces. Compared to industrial WC-6Co, NbC substrates multiply the tool life when machining carbon steel C45E and quenched and tempered steel 42CrMo4+QT. However, the current straight NbC inserts from laboratory scale with limited homogeneities displayed occasional premature tool failures.

By adjusting the metallurgy and processes including sintering cycles of NbC, significant gains in toughness and strength can be achieved and are scheduled for further investigation. The optimization of micro-geometry represents another important task for NbC. Additional steps focus on wear resistant tool coatings and tool geometry adjustments in order to obtain improved tool performance and enhance tool life and process stability.

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