Microstructural investigation and machining performance of NbC-Ti(C_{0.5}N_{0.5}) matrix cermets

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ABSTRACT

In this study, Ni or Co + Ni bonded NbC matrix cermets with secondary carbides (Mo₂C and WC) as well as Ti(C_{0.5}N_{0.5}) were prepared by liquid phase sintering at 1450°C in vacuum. Detailed microstructural investigation was performed by SEM, EPMA and XRD analysis. The microstructure, mechanical properties as well as the C45 (HB140) steel turning performance of the cermets were investigated, and compared with a commercial Ti(C_{0.5}N_{0.5}) based cutting insert. The sintering results indicated that the partial substitution of NbC by Ti(C_{0.5}N_{0.5}) had a significant effect on the core-rim microstructure and refinement of NbC solution grains, as well as improved mechanical properties of the NbC-Ti(C_{0.5}N_{0.5}) cermets. The phase constitution and composition of the cermets were supported by thermodynamic equilibrium calculations. All sintered cermets were composed of a fcc solid solution metal binder and a cubic core-rim (Nb,Ti,Mo,W)(C,N) solution phase, as well as an independent N-rich Ti(C,N) phase. The NbC-Ti(C_{0.5}N_{0.5}) and Ti(C_{0.5}N_{0.5}) matrix cermets had a comparable HV₃₀ of 1500-1600 kg/mm² and a similar fracture toughness of 8.0 MPa m^{1/2}.

Key words: Cermet, Niobium carbide, Carbonitride, Sintering, Mechanical properties

1. Introduction

The abrasion and chemical wear resistance of Ti(C,N)-based cermets are superior to that of WC-Co cemented carbides [1] and comprehensive reviews on Ni or Co bonded TiC/Ti(C,N) cermets have been published [2-4]. NbC offers the possibility to partially substitute WC in WC-Co cemented carbides [5, 6] or Ti(C,N) in Ti(C,N)-Ni based cermets [7, 8]. The microstructure and performance of Ti(C,N)-based cermets is considerably influenced by secondary carbide (WC/Mo₂C/NbC/TaC) additions [2]. The addition of a small amount of NbC or TaC to Ti(C_{0.7}N_{0.3})-Ni systems was reported to allow improving the interrupted cutting performance by retaining hot hardness and increasing the thermal shock resistance at elevated temperatures [8-10]. According to Qi et al, the addition of 5-40 wt% NbC

into a $\text{Ti}(\text{C}_{0.7}\text{N}_{0.3})$ -20 wt% Ni system had a clear effect on the core-rim structure of the carbonitride grains [8]. A $(\text{Ti,Nb})(\text{C,N})$ solid solution was formed around the undissolved $\text{Ti}(\text{C,N})$ grains in the presence of low amounts of NbC, whereas a rim structure formed around the NbC grains when the NbC content was above 10 wt% [8]. Due to the refined carbide grain size, reduced wear rates were observed for the $\text{Ti}(\text{C,N})$ -Ni cermets with 10 wt% WC, NbC or TaC additions [7]. Commercially available $\text{Ti}(\text{C,N})$ -based cermets can contain 7 to 22 wt% NbC [11].

On the other hand, NbC is hardly explored as a matrix carbide, but its physical and chemical properties show a high potential for wear and tribological applications [12,13]. It was recently reported, that pure NbC as well as metal bonded NbC have a pronounced wear resistance under dry sliding conditions versus other monolithic ceramics and carbides [14,15], and also increased tool life when compared to WC-Co inserts [16-18]. NbC based cermets are suitable for the machining of soft carbon steels, hardened gear steels and Al alloys [13]. Under a wet cooling condition, NbC-10Ni-12WC-14TiC tools presented a superior performance compared to commercially available WC-10Co-11TiC-2NbC (P10) grades when machining gear steel (AISI 4340, 34CrNiMo4, 42 ± 3 HRC) [13]. Lab scale produced NbC- $\text{Ti}(\text{C}_{0.7}\text{N}_{0.3})$ cermet tools showed a longer tool life than that of a much harder WC-6.5Co tool when dry turning of hardened 42CrMo4 gear steel at a speed of 150 m/min. Moreover, the NbC- $\text{Ti}_{0.7}\text{N}_{0.3}$ tools provided a superior surface quality (e.g. lower surface roughness) of the workpiece despite the longer cutting times [13]. Currently, there is no information available on the influence of $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ addition on the microstructure and mechanical properties of NbC-based cermets. In this study, NbC- $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ -Ni-Co-WC- Mo_2C cermets with 0-42 wt% $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ addition were processed to obtain NbC-Ni based cermets with refined ceramic grains and improved mechanical properties for cutting tool applications.

2. Experimental

2.1. Materials preparation

NbC (CBMM, FSSS=1.52 μm , Brazil), $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ (Langfeng, FSSS=1.05 μm , China), WC (Umicore, CW5300, FSSS=2 μm , Belgium), Mo_2C (Langfeng, FSSS=3.50 μm , China), Co (Umicore, Co-HMP, FSSS=0.55 μm , Belgium) and Ni (Vale, T123TM, FSSS= 3-7 μm , UK) powders were used to prepare the NbC cermets. The NbC powder has a total C and O content of 10.9 and 0.21 wt%. The $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ powder has a C, N and O content of 9.95, 11.2 and 0.55 wt%, respectively. The primary NbC grain size is in the submicrometer range, as shown in Fig. 1.a. The NbC powder agglomerates could be deagglomerated using a proper powder mixing process. The $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ powder, shown in Fig. 1.b, consists of submicrometer primary grains. The chemical composition of the investigated NbC cermets with different $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ contents are summarized in Table 1. The commercial $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ -6Co-6Ni-20WC-4 Mo_2C -3TaC grade is Xiamen Tungsten grade GN491. The theoretical density reported in

Table 1 was calculated based on the mixture rule, using the density of its compounds. The calculated binder content in vol% is also listed in Table 1.

Fig. 1. Morphology of the NbC (a) and $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ (b) starting powders.

Table 1 Chemical compositions of the investigated NbC- $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ based cermets

Grade	Composition (wt%)	Binder (vol%)	Theoretical density (g/cm^3)
9 Ni	NbC-9Ni-18WC	8.76	8.67
14 $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$	NbC-14 $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ -9 Ni-18WC	8.13	8.04
22 $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$	NbC-22 $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ -12 Ni-20WC-4 Mo_2C	10.61	7.87
32 $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$	NbC-32 $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ -7Co-7Ni-20WC-4 Mo_2C	11.81	7.56
42 $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$	NbC-42 $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ -7Co-7Ni-20WC-4 Mo_2C	11.27	7.16
Commercial	$\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ -6Co-6Ni-20WC-4 Mo_2C -3TaC	8.98	6.78

All powder mixtures were mixed on a multi-directional mixer (Turbula, WAB, Switzerland) in ethanol for 48 h using WC-6 wt% Co milling balls (Ceratizit grade H20C, $\varnothing 10$ mm). The suspension was dried in a rotating evaporator at 65°C . Cold isostatically pressed (200 MPa, EPSI) powder compacts were pressureless sintered for 90 min at 1450°C in vacuum (~ 20 Pa) at a heating rate of $3^\circ\text{C}/\text{min}$ in a graphite furnace. $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ containing NbC inserts were also produced according to the ISO TNMG160404 geometry for turning application testing. The cutting tool performance was assessed for dry longitudinal cylindrical turning of C45 (HB140) steel with a turning speed of 250 m/min, feed rate of 0.2 mm/rev and depth of cut (a_p) of 1 mm. Three cutting tests of each insert grade were performed. After continuously dry turning for 10 min, the maximum flank wear width (VB_{max}) was used to evaluate the wear resistance.

2.2. Characterization

The bulk density of the sintered cermets was measured in ethanol. High resolution microstructural images were obtained by NanoSEM (Nova 450, FEI). Elemental mappings of polished cross-sections were investigated by electron probe microanalysis (EPMA, JXA-8530F, JEOL Ltd, Japan), equipped with a wavelength dispersive analysis system. The beam current and accelerating voltage were fixed at 50 nA and 15 kV respectively. Phase identification in the sintered cermets was conducted by a θ - θ X-ray diffractometer (XRD, Seifert 3000, Ahrensburg, Germany) using Cu K α radiation (40 kV, 40 mA). For detailed X-ray diffraction pattern analysis, step-scan data (step size of 0.02°) of polished cermets were recorded in the 20-80° 2 θ range. Rietveld structural refinement analysis was performed to determine the lattice parameters of the carbide and binder phases [19]. The Vickers hardness, HV₃₀, was measured (Model FV-700, Future-Tech Corp., Tokyo, Japan) with an indentation load of 294 N for 15 s at room temperature. The Palmqvist indentation fracture resistance, K_{IC}, was calculated from the length of the radial cracks around the Vickers indentations, using the formula proposed by Shetty *et al.* [20]. The reported values are the mean and standard deviation of five indentations. Moreover, thermodynamic simulations were performed to estimate the phase constitution of the sintered cermets, using Thermo-Calc software [21] and a commercial Ni based database TCNI8.

3. Results and Discussion

3.1. Microstructure analysis

The backscattered electron (BSE) contrast microstructures of the NbC-9Ni-18WC (wt%) cermet are shown in Fig. 2. The bright and dark contrast grains correspond to the NbC and Ni binder, respectively. The 18 wt% WC addition is completely dissolved either in the carbide or in the binder grains. The liquid phase sintering condition resulted in a homogeneous Ni binder distribution. According to the atomic contrast, core-rim structure (Nb,W)C grains were formed in the cermet with a Nb-rich core and a W-containing rim. The (Nb,W)C grains with a grey core and brighter rim are formed by co-precipitation of dissolved W, Nb and C in the Ni binder on the non-dissolved NbC cores. Similar contrast core-rim structures have been reported for Ti(C,N) based cermets [4,22]. Secondary carbides (Mo₂C/WC/TaC/NbC) dissolve into Ni or Ni+Co binder and reprecipitate on undissolved Ti(C,N) cores to form a solid solution rim [23,24]. The dark cores are undissolved Ti(C,N) grains, whereas the rim is a (Ti/Mo/W/Ta/Nb)(C,N) solid solution.

Compared to the NbC starting powder, significant carbide grain growth is observed in the cermet during sintering. The average carbide grain size, as determined by the line intercept method, is 4.82 μ m in the 9Ni cermet. Due to the dissolution of WC in the binder and NbC grains, the surface energy of the liquid Ni binder, as well as the in-situ formed mixed carbide (Nb,W)C, was changed during

sintering, influencing the grain growth behaviour of the carbide. As compared to NbC-Ni cermets, a much smaller average NbC grain size is observed in the WC added NbC-Ni cermet [18].

Fig. 2. Backscattered electron micrographs of the NbC-9Ni-18WC (wt%) cermet, pressureless sintered for 90 min at 1450°C.

The microstructures of the NbC cermets with 14-42 wt% $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ are shown in Fig. 3. Only two contrasting grains, i.e. core-rim structured NbC solution grains and bright metallic binder were detected in the cermet with 14 wt% $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$, whereas additional dark contrast grains, identified as rimless N-rich $\text{Ti}(\text{C},\text{N})$ grains, were observed in the cermets with a higher $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ content (see Fig. 3.b-d). The partial substitution of Ni by Co in the current cermets does not result in a clear difference rimless structure of the N-rich $\text{Ti}(\text{C},\text{N})$ grains. With an increasing $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ content, the content of the rimless $\text{Ti}(\text{C},\text{N})$ grains is increased, whereas the rim thickness of the NbC solution grains is increased. It is known that core-rim structure of $\text{Ti}(\text{C},\text{N})$ cermets is influenced by the starting powder size, carbon/nitrogen content as well as sintering conditions [2, 4, 25]. With increasing N content in a $\text{Ti}(\text{C},\text{N})$ cermet system, the thermodynamic stability of $\text{Ti}(\text{C},\text{N})$ phase is increased and the affinity of W and Mo with N is decreased [4]. Therefore, some $\text{Ti}(\text{C},\text{N})$ grains exhibit rimless or incomplete rims when using a high N content $\text{Ti}(\text{C},\text{N})$ starting powder (such as $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$) or under a N_2 sintering atmosphere [2, 4]. On the other hand, thick rims on $\text{Ti}(\text{C},\text{N})$ grains can be formed at a high carbon activity, such as using $\text{Ti}(\text{C}_{0.7}\text{N}_{0.3})$ powder or a low $\text{N}/(\text{C}+\text{N})$ ratio [8, 26]. In this study, the observed rimless $\text{Ti}(\text{C},\text{N})$ grains in the 22, 32 and 42 $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ cermets is consistent with the microstructure of $\text{Ti}(\text{C}_{0.7}\text{N}_{0.3})$ -NbC-20 Ni (wt%) and $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ -WC-NbC-Co cermets [8,25]. A $(\text{Ti},\text{Nb})(\text{C},\text{N})$ rim was observed around the core $\text{Ti}(\text{C},\text{N})$ grains in the presence of 5 and 10 wt% NbC, whereas rimless $\text{Ti}(\text{C},\text{N})$ grains were observed in cermets with 15 and 40 wt% NbC addition [8].

With regards to the NbC solution grains, a white core and grayish rim structure in all the NbC cermets was observed. Elements of Nb, Ti, W and Mo are detected in these NbC solution grains. Due to the lower atomic mass of Ti compared to Nb, the darker rim area is richer in Ti than the brighter

core. On the other hand, the bright core has a higher concentration of W and Nb, as compared to the rim area. The microstructure of the solution carbide is commonly observed in conventional Ti(C,N) cermets with the addition of NbC, WC or Mo₂C [2, 4, 8].

In addition, N plays a very important role as a grain growth inhibitor. The carbide grain size in the Ti(C_{0.5}N_{0.5}) containing cermets was found to be much finer than for the NbC-9Ni-18WC cermet, with an average carbide grain size of 0.97 μm in the cermet with 14 wt% Ti(C_{0.5}N_{0.5}). The average carbide grain size only slightly decreased with an increasing Ti(C_{0.5}N_{0.5}) content.

Fig. 3. BSE micrographs of the 14Ti(C_{0.5}N_{0.5}) (a), 22Ti(C_{0.5}N_{0.5}) (b) 32Ti(C_{0.5}N_{0.5}) (c) and 42Ti(C_{0.5}N_{0.5}) (d) grade cermets, pressureless sintered for 90 min at 1450°C.

Fig. 4 demonstrates the elemental distribution in the NbC cermet with 32 wt% Ti(C_{0.5}N_{0.5}). The Co and Ni binder form a solution phase and are evenly distributed throughout the cermet microstructure. The binder however does not form an interconnected network. W and Mo is present in both the binder and carbide grains. However, a higher concentration of Mo was detected in the binder due to the higher solubility of Mo in Ni. Regarding the Ti distribution, the rim area of the NbC matrix grains had a higher concentration of Ti than the core. The composition of the rim area is related to the surface

energy of the carbide/nitride in the liquid binder. In general, the lower the solubility in a metal, the higher the surface energy of a substance [2]. The solubility of NbC, TiC, TiN, WC and Mo₂C in Ni at 1400°C is 7, 11, <0.5, 27 and 36 wt% respectively [27]. Therefore, the TiC-rich rim precipitated on the W and Nb-rich core reduced the overall surface energy of the system. Besides the NbC solution grains, the rimless Ti(C,N) grains, rich in Ti, C and N without Nb, W, Mo and Ni, are found in the cermet.

Fig. 4. Elemental distribution maps in the sintered NbC-32 Ti(C_{0.5}N_{0.5})-7Co-7Ni-20WC-4Mo₂C cermet.

The microstructure of the commercial Ti(C_{0.5}N_{0.5}) based insert is shown in Fig. 5. Both dark core-white rim and white core-dark rim grains are observed in the microstructure. The dark core-white rim grains are formed by the dissolution-reprecipitation mechanism [23-26,28,29]. During sintering, Ti(C,N) and secondary carbides (Mo₂C/WC/TaC/NbC) dissolve into the binder phase and reprecipitate on undissolved Ti(C,N) cores to form the white solid solution rim [23,24]. Therefore, the dark cores are undissolved Ti(C,N) grains with a (Ti/Mo/W/Ta)(C,N) solid solution brighter rim. On the other hand, the formation of the white core-dark rim grain structure can be divided into two stages. During the initial solid state sintering, W-rich (Ti,W,Ta,Mo)C grains are formed through the dissolution and precipitation of TiCN, WC, TaC and Mo₂C. During the later higher temperature liquid phase sintering step, (Ti,W,Ta,Mo)C relatively poor in Mo and W continues to precipitate on the W-rich (Ti,W,Ta,Mo)C core, resulting in the white core-dark rim structure [30].

Fig. 5. BSE micrographs of the commercial Ti(C,N)-based insert with Ti(C_{0.5}N_{0.5})-6Co-6Ni-20WC-4Mo₂C-3TaC (wt%) starting powder composition.

3.2. Phase analysis

The sintering and densification of Ti(C,N)-based cermets contain complex thermodynamics and kinetics phenomena. Many factors, such as alloy composition and sintering cycle, can have significant influence on the microstructure, phase constitution and properties of cermets. An integrated approach of thermodynamic calculations and experiments was successfully applied to investigate the gradient zone formation for Ti(C,N)-based cermets sintered in N₂ atmosphere [31]. In this study, thermodynamic simulation was performed to access the influence of Ti(C_{0.5}N_{0.5}) content on the phase constitution and phase composition of the NbC-Ti(C_{0.5}N_{0.5}) cermets. Co, Ni, WC, NbC, C, TiC and TiN were defined as input components for the calculation and the vacuum pressure is set as 100 Pa. Fig. 6.a shows the calculated phase constitution of the NbC-Ti(C_{0.5}N_{0.5}) cermets with 7Co+7Ni binder at 1450°C. The estimated phase constitution, i.e. the coexistence of NbC solution, Ti(C,N) and binder phases, is consistent with the observed microstructure in Fig. 3. It is clear that the content of the NbC solution and Ti(C,N) phases are dependent on the Ti(C_{0.5}N_{0.5}) content. With increasing Ti(C_{0.5}N_{0.5}) content, more and more Ti(C,N) phase is formed, whereas the amount of NbC solution phase is decreased. Experimental study by XRD phase analysis indicated that the sintered NbC-Ti(C_{0.5}N_{0.5}) cermets contained a fcc solid solution binder and cubic NbC solution phase when the Ti(C_{0.5}N_{0.5}) content is less than 14 wt%. An additional Ti(C,N) phase was detected when the Ti(C_{0.5}N_{0.5}) content increased to 22, 32 and 42 wt%. Although the core-rim NbC solution grains were observed in the cermets, the XRD analysis is not able to identify the individual XRD peak positions of the rim and core of the NbC solution phase due to a very close phase composition and identical crystal structure of the rim and core area.

Fig. 6.d shows the influence of the Ti(C_{0.5}N_{0.5}) content on the measured lattice parameters of the NbC solution and Ti(C,N) phases. With regards to the NbC solution phase, the lattice parameter decreases with increasing Ti(C_{0.5}N_{0.5}) content due to an increasing substitution of Nb (146 pm) atom by

smaller atomic radius elements, such as W (139 pm) and Ti (144.2 pm). This result can be also explained by the calculated phase composition, as presented in Fig. 6.b. With increasing $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ content, more and more NbC is substituted by TiC, WC and Mo_2C , resulting in a decreased lattice parameter of the NbC solution phase. According to the calculation, it is noted that the NbC solution phase has a very low TiN content. On the other hand, the rimless $\text{Ti}(\text{C},\text{N})$ phase retains a very high N content in order to keep the N mass balance in the system, as seen in Fig. 6.c. The lattice parameter of the $\text{Ti}(\text{C},\text{N})$ phase, as shown in Fig. 6.d, varies slightly with the $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ content, indicating a very close C/N ratio of the $\text{Ti}(\text{C},\text{N})$ phase.

Fig. 6. Influence of the $\text{Ti}(\text{C}_{0.5}\text{N}_{0.5})$ content on the phase constitution of the investigated cermets (a), composition of the NbC solution phase (b), composition of the $\text{Ti}(\text{C},\text{N})$ phase (c) and the lattice parameter of the NbC solution and $\text{Ti}(\text{C},\text{N})$ phases (d).

3.3. Mechanical properties

Table 2 summarizes the density, Vickers hardness (HV_{30}) and indentation fracture toughness of the cermets are summarised in All sintered cermets were fully densified. It is clear that the hardness of the

NbC based cermets is closely related to the NbC grain size and the binder content. At a binder content of 9 wt% Ni, a significant increase in hardness of nearly 300 kg/mm² was measured upon adding 14 wt% Ti(C_{0.5}N_{0.5}), as compared to the NbC-9Ni-18WC (wt%) cermet. On the other hand, the fracture toughness decreases with decreasing carbide grain size from 9.5 to 7.9 MPa m^{1/2}. For the NbC-Ti(C_{0.5}N_{0.5}) cermets, the hardness is generally in the 1530 to 1580 kg/mm² range, varying slightly with the Ti(C_{0.5}N_{0.5}) content. The fracture toughness is in the range of 7.7 to 8.2 MPa m^{1/2}. A comprehensive overview of hardness, toughness and flexural strength on Ti(C,N) based cermets is reported in the work [4]. A combination of 1500 HV₁₀ and 8 MPa m^{1/2} K_{IC} is commonly found in commercial Ti(C,N) based cermets [4]. Therefore, it is interesting to investigate the cutting performance of the NbC-Ti(C_{0.5}N_{0.5}) cermets.

Table 2 Hardness and fracture toughness of the NbC based cermets

Grade	Binder (vol%)	Density (g/cm ³)	NbC grain size (μm)	HV ₃₀ (kg/mm ²)	K _{IC} (MPa m ^{1/2})
9 Ni	8.76	8.66	4.82	1234 ± 12	9.5 ± 0.2
14 Ti(C _{0.5} N _{0.5})	8.13	7.98	0.97	1531 ± 14	7.9 ± 0.1
22 Ti(C _{0.5} N _{0.5})	10.61	7.89	0.88	1552 ± 7	7.7 ± 0.1
32 Ti(C _{0.5} N _{0.5})	11.81	7.45	0.83	1536 ± 7	7.9 ± 0.1
42 Ti(C _{0.5} N _{0.5})	11.27	7.09	0.87	1587 ± 13	8.2 ± 0.1
Commercial	8.98	6.78	/	1582 ± 15	8.1 ± 0.1

3.4. Machining performance

It is well known that TiCN-based cermets proves to be superior to uncoated WC-Co cemented carbides with regard to their abrasion and chemical wear resistance [32-34]. In the present study, the dry turning performance of C45 (HB140) steel with the NbC-Ti(C_{0.5}N_{0.5}) inserts (TNMG 160404) is directly compared with a commercial Ti(C_{0.5}N_{0.5}) based cermet. Fig. 7 shows the maximum flank wear width, VB_{max}, after 10 minutes dry turning (depth of cut a_p= 1,0 mm; f= 0,15 mm/rev, v= 250 m/min). Each value given in Fig. 7 is the average and standard deviation of three turning tests from three different inserts. The cutting performance of the NbC-Ti(C_{0.5}N_{0.5}) inserts is mainly driven by the Ti(C_{0.5}N_{0.5}) content, which controls the resistance to adhesive and abrasive wear [35]. The 32 and 42 Ti(C_{0.5}N_{0.5}) inserts exhibited a lower flank wear than the commercial Ti(C_{0.5}N_{0.5}) based insert. A comparable small crater wear was observed in the 42 Ti(C_{0.5}N_{0.5}) insert and commercial insert.

Fig. 7. Maximum flank wear after 10 minutes of dry turning of C45 (HB140) steel.

Fig. 8 visualize the morphology of the flank surfaces of the TNMG inserts. The lower flank wear width is seen for the grades 32Ti(C_{0.5}N_{0.5}) and 42Ti(C_{0.5}N_{0.5}) with an associated more even surface. The wear volume on the flank edges over their total length of wear scar were determined by using 3D-profilometry with a confocal microscope. In comparison to the commercial grade, the wear volume is half for 32Ti(C_{0.5}N_{0.5}) and 42Ti(C_{0.5}N_{0.5}) grade. The resistance to flank wear, generally related to the abrasion resistance of the tool and directly correlated to the insert hardness, of the investigated inserts does not follow their hardness trend. The addition of NbC or TaC has been reported to be beneficial for the Ti(C,N) cermet tool life by increasing the hot hardness and thermal shock resistance [35]. A higher hot hardness is therefore expected for the 32 and 42 Ti(C_{0.5}N_{0.5}) inserts, resulting in a better flank wear resistance than that of the commercial insert.

Fig. 8. Morphology of the worn flank edges of the TNMG 160404 inserts, commercial insert (a), 22Ti(C_{0.5}N_{0.5}) (b), 32Ti(C_{0.5}N_{0.5}) (c) and 42Ti(C_{0.5}N_{0.5}) (d) cermets.

4. Conclusions

Full densification of Ni or Ni+Co bonded NbC based cermets with up to 42 wt% Ti(C_{0.5}N_{0.5}) was achieved by pressureless liquid phase sintering in vacuum for 90 min at 1450°C. The WC and Mo₂C, as well as Ti(C_{0.5}N_{0.5}) starting powders completely dissolved in the NbC and binder phases during sintering. Residual N-rich Ti(C,N) was present in the cermets containing 22-42 wt% Ti(C_{0.5}N_{0.5}).

The NbC grain morphology and size were dependent on the added carbides and Ti(C_{0.5}N_{0.5}) content. Core-rim structured niobium carbide grains with a Nb- and W-rich core and a Ti-rich rim were formed in the cermets with WC and Ti(C_{0.5}N_{0.5}) addition. The change in the lattice parameters also confirmed the dissolution of WC, Mo₂C and Ti(C_{0.5}N_{0.5}) in the metal binder as well as the NbC phase. The addition of Ti(C_{0.5}N_{0.5}) was able to reduce the NbC grain growth during liquid phase sintering, compared to the NbC-Ni-WC equivalents. A fine core-rim structured NbC grain size of 0.80-0.90 µm was obtained in the cermets with 14-42 wt% Ti(C_{0.5}N_{0.5}).

A Vickers hardness of 1530-1580 kg/mm² and fracture toughness of 7.7-8.2 MPa m^{1/2} were obtained for the NbC-Ti(C_{0.5}N_{0.5}) cermets. The flank wear during dry turning of C45 steel decreased with increasing Ti(C_{0.5}N_{0.5}) content. The 32 and 42 wt% Ti(C_{0.5}N_{0.5}) containing NbC-based inserts bonded with Co and Ni exhibited a respectively comparable or lower flank wear than a commercial Ti(C_{0.5}N_{0.5})-based insert with similar mechanical properties.

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