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DRY MACHINING USING NOVEL CHROMIUM BASED COATINGS

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Abstract:
High speed cutting and dry machining are two currently discussed research topics for reducing production costs in metal cutting industry. Physical vapour deposition (PVD) coatings for cutting tools play an important role for making both technologies possible. The current study discusses the drawbacks and opportunities of new chromium-based coatings for dry machining applications.

In order to find improved coatings, both tribological and practical wear tests of coated steel specimens and WC/Co tools were performed. The characterization of the coatings includes fundamental properties such as thickness, hardness, coating composition, and adhesion quality. Dry turning operations were performed in order to study the wear behaviour. The wear properties of Cr_xAl_yN and $Cr_xAl_ySi_zN$ coatings were compared to uncoated tools in turning of cast iron and aluminium alloy. The results show that the incorporation of silicon increases the wear and oxidation resistance as well as the micro hardness.

Key Words: Dry Machining, PVD Coating, CrAlN, Tribology

1. INTRODUCTION

"High or Dry" could be the motto of current research in the field production engineering. Both high speed cutting and dry machining increase the mechanical and thermal loads on the cutting edge. As a result, adhesion, abrasion, diffusion, and oxidation of the cutting tool are also accelerated [1, 2]. In order to meet the new requirements of high speed cutting and dry machining, wear resistant soft and / or hard tool coatings are usually applied [3, 4].

Titanium-based coatings, especially (Ti,Al)N, are industrial state-of-the-art tool coatings for most machining operations [5]. They are characterized by high hardness and wear resistance even at elevated temperatures [6-9]. Adding chromium to a (Ti,Al)N coating system further increases the performance towards improved oxidation- and corrosion-resistance [7-10].

Since the incorporation of chromium to titanium based coatings enhanced the coating microstructure [11, 12], (Cr,Al)N coatings exhibited promising results in dry machining applications [13]. Jin et al. indicated that the incorporation of rare earth elements like yttrium into the TiN or TiAlN lattice can improve thermal properties, interfacial adhesion, and corrosion resistance [14, 15]. Small amounts of silicon were also found to improve the mechanical properties for such coatings [16, 17]. In this paper the influence of silicon on the tribological wear properties, the coating properties, and the performance in dry machining of cast iron and aluminium alloy using CrAlN-based coatings is discussed.

2. EXPERIMENTAL

2.1 Coating technology

All coatings for the machining tests as well as the scratch tests were sputtered onto WC/Co hard metal inserts. The specimens for the GDOES (glow discharge optical emission spectrometry) analyses and micro hardness measurement were deposited on notched bar impact steel (Ck45, DIN 1.1191, AISI 1045) specimens. The Cr_xAl_yN- as well as the $Cr_xAl_ySi_zN$- PVD coatings were deposited in a commercial PVD magnetron sputter unit from Alcatel (SCM 601) at 300 °C. The SCM unit is equipped with one magnetron cathode in a face-to-face arrangement to the substrates at a distance of 100 mm. The target was made of pure chromium. An aluminium ring was mounted into the sputter erosion crater of the target to achieve a fixed aluminium content in the coatings. Small granules of the additional silicon were positioned in the same manner onto the target. By increasing the weight of the additional granules, the silicon content was varied up to 6 at.%. Pure nitrogen gas was used to deposit both Cr_xAl_yN and $Cr_xAl_ySi_zN$. The adjusted power was 750 W, the gas pressure before deposition was $4 \cdot 10^{-4}$ Pa and the total pressure during deposition was 1.5 Pa.

The substrates were cleaned with ultrasonic assistance and rinsed with *n*-heptane before application to the PVD chamber. Prior to deposition, the samples were etched with Ar+ ions at a bias voltage of -600 V for 30 min. The targets were preheated for a duration of 5 min. During the first half of the deposition, the bias voltage was kept at -200 V to achieve good adhesion; during the second part, the bias voltage was reduced to -30 V.

2.2 Coating characterization using GDOES

The analytical glow discharge measurements (GDOES) were carried out using a Spectro GDA 750 spectrometer and certified reference materials from BAM, Pechiney, NBS, Breitländer, and IARM. The system is equipped with a "Grimm type" glow discharge source. To perform the measurements on the notched bar impact specimens, a discharge source of 2.5 mm (GDS) diameter and a DC excitation mode was used.

2.3 Hardness, thickness and oxidation resistance

The Martens Hardness $HM_{0.1}$ was measured with an ultra-micro-hardness tester Shimadzu DUH 202 using a Vickers shaped diamond in accordance to DIN EN ISO 14577. The dependence of force and indentation depth was analyzed at a maximum load of 0.1 N. The given results are based on an average of six tests. The coating thickness was measured with a ball cratering test according to DIN V ENV 1071-2 for the $Cr_xAl_ySi_zN$ coatings and via GDOES measurement for Cr_xAl_yN. Oxidation resistance was measured by annealing the specimens at 800 °C in air for one hour.

2.4 Scratch test / coating adhesion

Besides thickness and hardness, the quality of the coating-substrate compound is of high interest for reliability in use. Therefore, investigations on adhesion and cohesion of the systems were made on the respective coated carbides. For the scratch adhesion testing a CSEM Revetest setup was used, which is in conformity with DIN V ENV 1071-3. Both the acoustic emission (AE) and tangential force were recorded while a Rockwell C diamond was drawn over the coatings with increasing normal force (10 N/mm, L_{max} = 100 N) at a speed of 10 mm/min. By comparing the critical loads L_{c1} and L_{c2} of the different coatings, it is possible to describe the coatings' adhesion quality. The value L_{c1} determines the load, where the first coating cracks could be detected during the scratch test; L_{c2}, respectively, is the force, where the first coating de-bonding is present.

2.5 SEM analyses

The morphology of the investigated coatings were examined using a Zeiss DSM962 microscope. Sawing the steel specimens with a diamond tipped wire saw close to the coating surface produced the cross sections. The specimens were then cooled with liquid nitrogen and brocken with a pendulum to produce a clearly broken surface, which was then analysed by SEM.

2.6 Dry machining tests

The cutting tests were performed on a turning lathe Boehringer VDF 180C, which has a power of 25 kW and up to 5,000 rpm. The experimental setup included the measurement of cutting forces, surface quality, and tool wear in order to characterize the machining properties of the new chromium-based coatings.

The cutting forces were measured using a 3-component dynamometer (type: 9067) from Kistler. The output signals from the dynamometer were transformed into analogue voltage signals linear to force, which were sampled by a transient recorder using a sampling rate of 5 kHz. Surface roughness was measured with a portable profilometer M2 from Mahr GmbH. A digital video microscope Smartscope MVP 250 from OGP GmbH was used to determine the tool life, i. e. the width of flank wear in accordance to ISO 3856, optically.

The chosen experimental procedure included short tests in turning in order to find improved coatings for dry machining applications. The short tests were restrained to a tool path i. e. overrun length of approx. L_f = 1 m and conducted completely dry. Two types of workpiece materials were used: Spheroidal cast iron (GJS-500, DIN 0.7050) and aluminium alloy (EN AC-AlSi12CuNiMg, EN AC-48000). The mechanical properties of these work piece materials are given in Table I.

Table I: Typical mechanical properties of the work piece material used for the dry machining test.

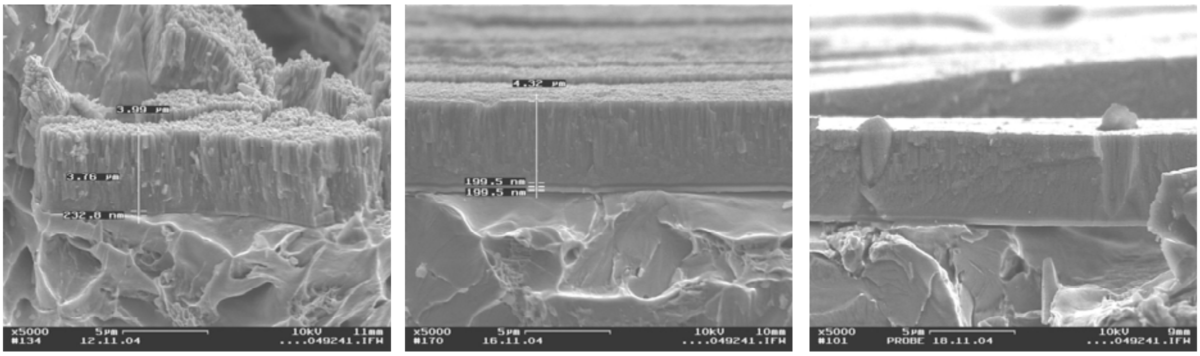
Work piece material	Tensile Strenth [MPa]	Yield strength [MPa]	Elonga tion [%]	Hardness HV_{10} [-]
GJS-500	500	320	7	350
EN AC-AlSi12CuNiMg	180 - 240	90 - 120	2 - 4	140

3. RESULTS

3.1 Coating composition and structure

Except for the amount of additives in the $Cr_xAl_ySi_zN$ and the ratio of Cr to Al in the Cr_xAl_yN coatings, all coating parameters were kept constant during the test series. However, the resulting coating thickness varied between 2.2 and 9.0 µm for the Cr_xAl_yN coatings, and 4.2 and 4.6 µm for $Cr_xAl_ySi_zN$, respectively; this variation is due to the rather experimental set-up using a deposition unit from Alcatel with only one horizontal target. Since both the alumium ring and the additive granules were simply fit onto the target, the electrical conductivity between these elements is constant in between certain limits. Using a sintered target with a fixed ratio of different elements in the target would be a better solution, however, not be easily applicable in a lab scale.

As it can be seen in Table II, the coating structure is crucial for the coatings' micro hardness: With increasing the amount of silicon, the coatings' hardness increases. This is due to a refinement in the microstructure of the coating as see in Figure 1. A comparison to the hardness values of the Cr_xAl_yN coatings is problematic, due to the difference in coating thickness. Both coatings, however, exhibit high hardness values.



$Cr_{24}Al_{16}Si_1N_{40}$ $Cr_{23}Al_{16}Si_3N_{36}$ $Cr_{22}Al_{13}Si_6N_{36}$

Figure 1: SEM pictures of fracture surface of CrAlSiN coated CK45 specimens.

The most crucial value for dry machining i. e. oxidation resistance was found best for the $Cr_{23}Al_{16}Si_3N_{36}$ coating, since an oxide layer forms on top of the coating, thus acting as a protective layer. This finding was supported by the GDOES measurements of both as-depoitioned and annealed coatings.

Both $Cr_xAl_ySi_zN$ coatings with 1 and 6 at.% Si exhibit a significant decrease in coating thickness after annealing (see Table II). This decrease is attributed to oxidation phenomena on the surface of the coating.

Table II: Mechanical characterisation of the coating.

Coating	Weight of Si granules	Content [at.%]				L_{c1} [N]	L_{c2} [N]	$HM_{0.1}$ [GPa]	.1.11 Thickness [µm]	
		Al	Cr	Si	N				As deposited	Tempered at 800°C
uncoated WC/co	-	-	-	-		-	-	15.46	-	-
$Cr_{12}Al_{15}N_{58}$	-	12	15	-	58	-	-	15.3	2.2	-
$Cr_{20}Al_{60}N_{19}$	-	20	60	-	19	-	-	7.6	9.0	-
$Cr_{24}Al_{16}Si_1N_{40}$	1g Si	16	24	0.9	40	38.0	46.6	7.2	4.5	3.2
$Cr_{23}Al_{16}Si_3N_{36}$	2g Si	16	23	3.3	36	17.6	38.8	9.6	4.6	4.7
$Cr_{22}Al_{13}Si_6N_{36}$	5g Si	12	22	6.4	36	16.4	30.6	11.4	4.2	3.5

The coatings' composition, as given in Table II, shows that an increasing amount of silicon decreases the critical load of the coatings. This is probably a result of the increased micro hardness. Since both good adhesion and high hardness are necessary for cutting tools, this problem can be solved by using a CrN or TiN intermediate layer acting as a adhesion negotiator. However, the fabrication of such a layer is not possible with the used deposition unit form Alcatel.

3.2 Dry machining results

The dry machining characteristics of cast iron and aluminum alloy show differences in their wear behaviour using CrAlN, CrAlSiN coated and uncoated carbides. Turning of cast spheroidal iron is mainly characterized by abrasive wear with discontinuous chips, whereas the used temperable aluminium alloy imposes lower temperatures, continuous long chips and adhesion wear onto the cutting edge.

A cylindrical test tube (∅ 140 mm x 200 mm) was used for the dry turning tests of GJS-500. The machining results show, that the chromium-based tools have a high potential for dry machining. As presented in Figure 2 both the Cr_xAl_yN and $Cr_xAl_ySi_zN$ coated tools are subject to decreased flank wear compared to the uncoated tool. Concerning the variation of silicon content, the following can be resumed: Small amounts of silicon of up to 3 at.% enhance the dry machining properties, whereas a further increase diminish the performance below the level of the $Cr_{12}Al_{15}N_{58}$ coating. The latter was the best coating in previous studies [13]. Although it was found, that the grain structure is refined by additional silicon (see Fig. 1), the adhesion quality is not sufficient to endure the thermal and mechanical loads during dry machining. The best coating for dry cutting in the given tests is the coating with 3 at.% Si.

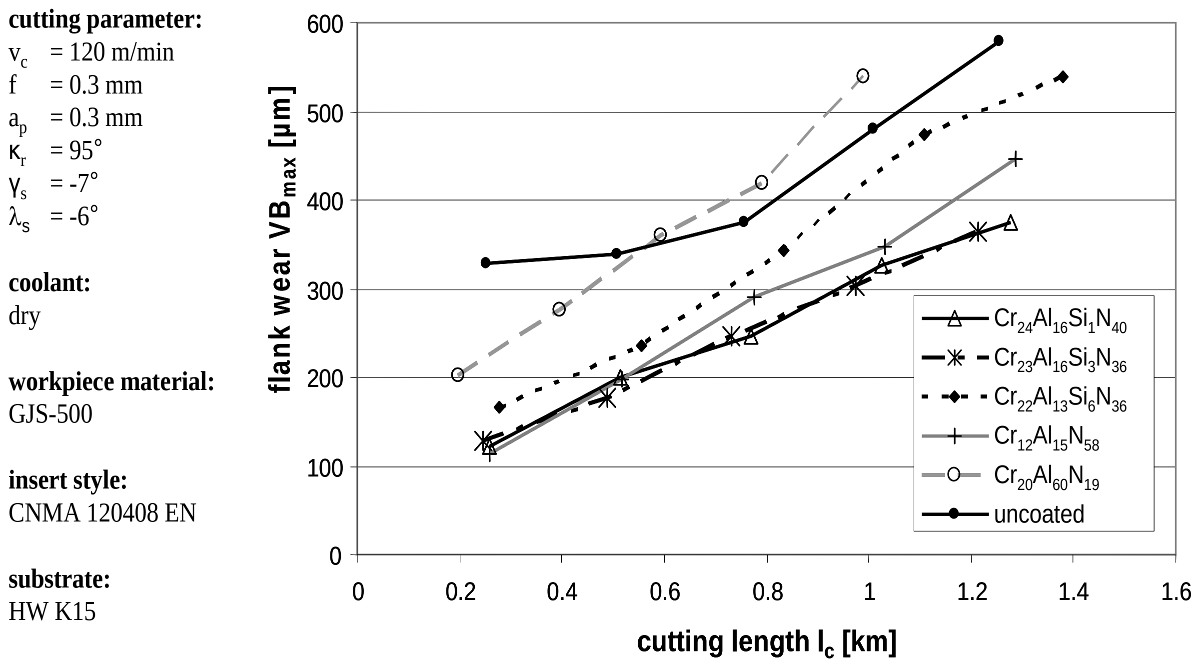


Figure 2: Development of flank wear versus cutting length for WC/Co coated tools in dry machining of spheroidal cast iron.

With respect to the measured cutting forces F_c Figure 4 shows the following: The cutting forces of all coatings initially decrease after the first cut, which is due to increased tool wear. However, the cutting forces of the uncoated and $Cr_{12}Al_{15}N_{58}$ coated tool are higher than the newly developed $Cr_xAl_ySi_zN$ coatings. Consistent with the findings above, the coatings with 1 and 3 at.% exhibit the lowest cutting forces.

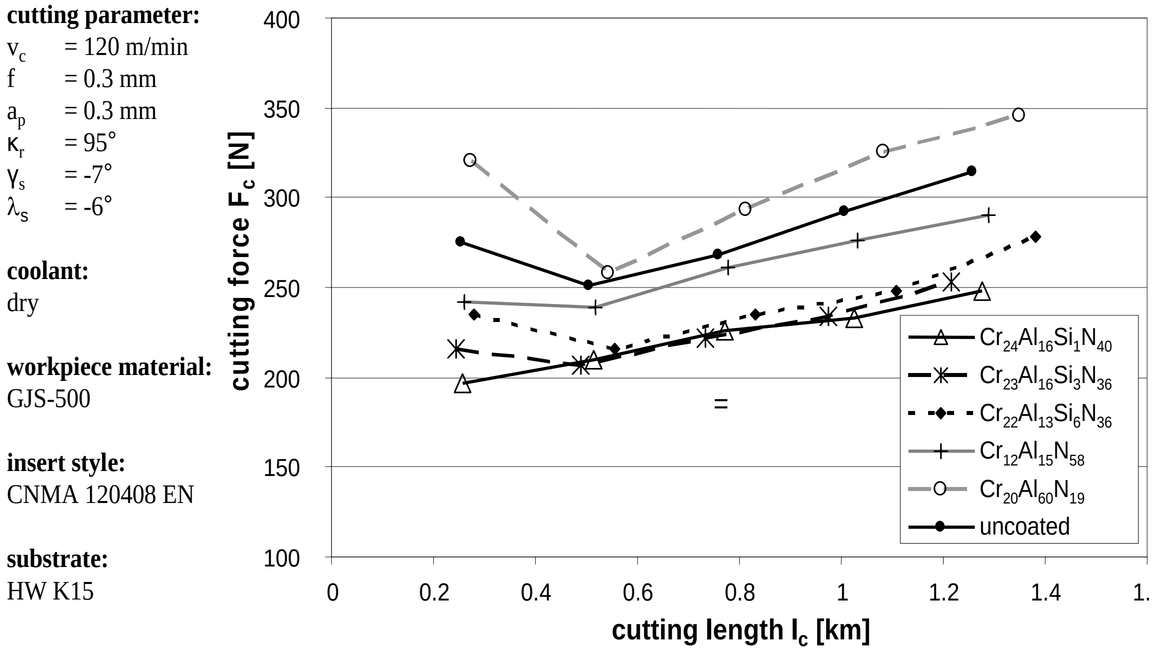


Figure 3: Development of cutting force versus cutting length for WC/Co coated tools in dry machining of spheroidal cast iron.

The dry machining tests with EN AC-AlSi12CuNiMg aluminium alloy were conducted using a ∅ 100 mm x 430 mm specimen. The dry machining characteristics of the aluminium alloy, differs from the GJS-500 results (Figure 4).

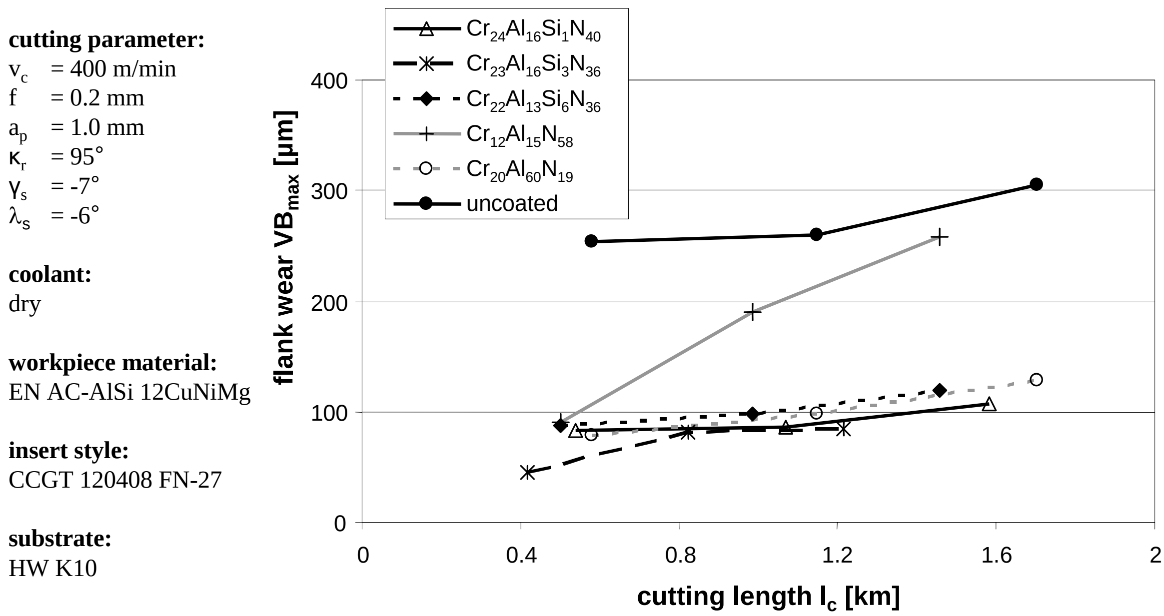


Figure 4: Development of flank wear versus cutting length for WC/Co coated tools in dry machining of an aluminium alloy.

First, the wear behaviour of the $Cr_{20}Al_{60}N_{19}$ is on the same level like the other coated tools. Secondly, the $Cr_{12}Al_{15}N_{58}$, which showed a good performance in machining GJS, exhibits extended tool wear probably due to high adhesive wear. In consistence with the findings above, the Si containing coatings increase the wear resistance compared to the uncoated tool. The analyses of the cutting forces show no significant difference and were therefore omitted.

4. DISCUSSION AND CONCLUSIONS

Compared to the results published previously [13, 18], the possibilities and limitations of using CrAlN based coatings for dry machining applications become clearer. Compared to uncoated tools, the use of chromium-based tool coatings enhances the performance of the cutting tools and might have sufficient potential to become an alternative to the state-of-the-art TiAlN coating. As shown above, it was possible to improve the coating structure by adding silicon to the coating system, thus increasing micro hardness, oxidation resistance, and adhesion quality compared to Cr_xAl_yN coatings. Since it is possible, to improve the coating systems further by optimized pre- and post treatments [6, 19-24], $Cr_xAl_ySi_zN$ coatings are an encouraging alternative to state-of-the-art coatings.

However, the full potential of CrAlSIN coatings cannot be utilized, until the adhesion quality is improved for silicon contents of 6 at.%, where the highest hardness was found. In comparison of dry machining of the two work piece materials, it can be concluded, that chromium based coatings are better suited for machining aluminium alloys, than for cast iron. Subsequent tests until the end of tool life will have to show the full potential of chromium based coatings.

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