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Mechanical and tribological behavior of silicon nitride and silicon carbon nitride coatings for total joint replacements

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Abstract

Total joint replacements currently have relatively high success rates at 10-15 years, however increasing ageing and an active population places higher demands on the longevity of the implants. A wear resistant configuration with wear particles that resorb *in vivo* can potentially increase the lifetime of an implant. In this study, silicon nitride (Si_xN_y) and silicon carbon nitride ($\text{Si}_x\text{C}_y\text{N}_z$) coatings were produced for this purpose using reactive high power impulse magnetron sputtering (HiPIMS). The coatings are intended for hard bearing surfaces on implants. Hardness and elastic modulus of the coatings were evaluated by nanoindentation, cohesive, and adhesive properties were assessed by micro scratching and the tribological performance was investigated in a ball-on-disc setup run in a serum solution. The majority of the Si_xN_y coatings showed a hardness close to that of sintered silicon nitride (~18 GPa), and an elastic modulus close to that of cobalt chromium (~200 GPa). Furthermore, all except one of the Si_xN_y coatings offered a wear resistance similar to that of bulk silicon nitride and significantly higher than that of cobalt chromium. In contrast, the $\text{Si}_x\text{C}_y\text{N}_z$ coatings did not show as high level of wear resistance.

Keywords: silicon nitride, silicon carbon nitride, coatings, total joint replacements, biotribology.

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1. Introduction

Total joint replacements have relatively high success rates at 10-15 years ([Garellick et al., 2011](#)). However, as the population gets older and more active, higher demands are placed on the implants. Several types of bearing couples are used in hip replacements, such as metal-on-polymer, metal-on-metal, ceramic-on-ceramic, and ceramic-on-metal. The metal-on-polymer bearing is the most common configuration, using cobalt chromium alloy (CoCr) on ultra-high molecular weight polyethylene (UHMWPE). However, wear particles from UHMWPE may induce an inflammatory reaction, which may lead to bone resorption and loosening of the implant ([Ingham and Fisher, 2005](#)). The release of metal ions is also a reason for concern due to toxicity ([Sargeant and Goswami, 2007](#)). Furthermore, a risk of catastrophic failure arises when bulk ceramics are used, due to their brittleness. In order to avoid this, the ceramic can be used as a coating on a more ductile (metal) substrate. Advantages with coatings can include reduced wear rates and an increased corrosion resistance ([Lappalainen and Santavirta, 2005](#)). A reduced amount of metal ion release would naturally be of great interest. Different surface treatments and coatings have been investigated for the bearing surfaces between the femoral head and the acetabular cup in hip implants, such as TiN ([Harman et al., 1997](#); [Pappas et al., 1995](#); [Teresa Raimondi and Pietrabissa, 2000](#)), diamond-like carbon ([Affatato et al., 2000](#); [Fisher et al., 2002](#); [Lappalainen et al., 1998](#)), CrN ([Fisher et al., 2002](#)), CrCN ([Fisher et al., 2002](#)), ZrO₂ ([Yen et al., 2001](#)), and Al₂O₃ ([Yen and Hsu, 2001](#)). However, insufficient adhesion and coating artifacts, such as droplets, have been reported as major concerns for these coatings.

During the last decades silicon nitride has been investigated for and introduced into the biomedical field. Traditionally, it has been used in engines, cutting tools, and ball bearings for its high mechanical performance ([Riley, 2000](#)). Today, silicon nitride is used for spinal implants and in early 2011 the first silicon nitride femoral head was implanted in USA. The choice of silicon nitride as an implant material is motivated by its excellent biocompatibility, low wear rates as well as relatively high fracture toughness and strength ([Mazzocchi and Bellosi, 2008](#); [Mazzocchi et al., 2008](#); [Sonny Bal et al., 2008, 2009](#)).

Furthermore, silicon nitride particles dissolve in aqueous media ([Laarz et al., 2000](#)). This, in turn, suggests that wear particles can dissolve *in vivo*, which may reduce the negative body response from the debris, and potentially increase the longevity of the implant. Additionally, density functional theory (DFT) calculations have shown that small amounts of substitutionally-bonded carbon can destabilize crystalline Si_3N_4 , indicating the possibility to tune the dissolution rate ([Olofsson et al., 2012](#)). To this date, there have only been a few publications on silicon nitride (Si_xN_y) and silicon carbon nitride ($\text{Si}_x\text{C}_y\text{N}_z$) coatings for joint implants ([Olofsson et al., 2012](#); [Shi et al., 2011, 2012](#)). Olofsson et al. (2012) used reactive radio frequency (r.f.) sputtering to produce Si_xN_y and $\text{Si}_x\text{C}_y\text{N}_z$ coatings that showed a potential for high wear resistance, but issues with coating defects and poor adhesion leading to flaking off of the coatings were reported. Shi et al. (2011) also used different magnetron sputtering methods for fabricating Si_xN_y and $\text{Si}_x\text{C}_y\text{N}_z$ coatings; r.f., direct current and unbalanced magnetron sputtering. However, adhesive properties of the coating were not reported.

In this study, Si_xN_y and $\text{Si}_x\text{C}_y\text{N}_z$ coatings were deposited using high power impulse magnetron sputtering (HiPIMS). Owing to high plasma densities and increased ionization probabilities, HiPIMS has been reported to produce dense coatings on complex structures ([Alami et al., 2005](#)). In addition, HiPIMS can be used to obtain increased adhesion between coating and its substrate ([Sarakinis et al., 2010](#)). In order to assess the mechanical properties and the durability of the coatings, hardness and elastic modulus were studied by nanoindentation, while cohesive and adhesive failure were investigated with micro scratching. The tribological properties, friction and wear resistance were studied in a ball-on-disc setup.

2. Materials and Methods

2.1. Coating deposition

Conventional P-doped Si (001) (Semiconductor Wafer, Inc) was used as substrate material for all coatings, due to its availability and the preliminary nature of the study. Additionally, three of the coatings were deposited on cobalt chromium (CoCr, ASTM F75, Sandvik AB, Sweden). The substrates were cleaned in 5 min sequences, first in acetone then in ethanol, and dried in N_2 gas before

deposition. The coatings were deposited using the industrial coating system CC800/9 ML (CemeCon, Germany) with rectangular targets (50×8.8 cm). The deposition process took place in power controlled HiPIMS mode using a pulse width of 200 μ s, at a frequency of 300 Hz. The reactive sputter process was carried out with an Ar/N₂-flow ratio of 0.16. For the Si_xN_y coatings, a silicon target (purity 99.999%) was used. During the deposition process the substrates faced the target at a distance of 6 cm. Si_xC_yN_z coatings were produced by co-sputtering from a silicon target and a graphite target (purity 99.5%). Here, the samples were rotated to pass both targets at the same target-to-substrate distance as for the Si_xN_y coatings. This sample rotation causes the formation of Si- and C-monolayers with a thickness below 10 nm. A negative bias voltage of -100 V was applied during the deposition. No pre-sputtering of the substrate was performed before the coating deposition. In order to alter the composition of the coatings, the following parameters were varied; the substrate temperature (110 °C, hereinafter denoted 'l' for low, and 430 °C, denoted 'h' for high), the Si target power (1-4 kW), C-target power (0-1.4 kW or absent for Si_xN_y coatings), as well as a stationary deposition for Si_xN_y coatings and sample rotation for Si_xC_yN_z coatings. Hence, the coatings are referred to using these variations, for example SiCN (4/0.5/h) intend a Si_xC_yN_z coating deposited with a Si target power of 4 kW, a C target power of 0.5 kW and a substrate temperature of 430°C. When no C-target was used, this is indicated by '-', e.g. SiN (1/-/l), which is a Si_xN_y coating deposited at a silicon target power of 1 kW, with no C-target and a substrate temperature of 110°C. The C content was estimated by energy dispersive spectroscopy analysis (EDS, EDAX Microanalysis, Netherlands) integrated in a scanning electron microscopy (SEM), at an acceleration voltage of 5 kV to obtain a surface sensitive measurement. The stationary deposited Si_xN_y coatings were thicker (1.2-4.4 μ m) than the Si_xC_yN_z coatings (0.4-0.9 μ m).

2.2. Mechanical characterization

Two bulk materials were used as references: CoCr (ASTM F75, Sandvik AB, Sweden, R_a ~8 nm) and Si₃N₄ (Keranova AB, Sweden, R_a ~15 nm). Hardness and elastic modulus of the reference materials and the coatings were obtained using a commercial nanoindenter (CSM Instruments UNHT, Switzerland) with a Berkovich tip. A total of 30 indents per sample were completed varying the

maximum load to obtain an approximate indentation depth of 40 nm. Hardness and elastic modulus were calculated using the Oliver-Pharr method ([Oliver and Pharr, 1992](#)). The elastic modulus was determined for the coatings and for the reference Si₃N₄ using a Poisson's ratio of 0.25 ([Walmsley et al., 2007](#)), whereas for CoCr a Poisson's ratio of 0.3 was assumed.

Scratch tests were performed using a micro scratcher (CSM Instruments UNHT, Switzerland) with a sphero-conical stylus (apex 90°; tip radius 2 µm). A progressive load up to 300 mN over 600 µm (loading rate 150 mN/min) was applied. Additional pre- and post-scans were carried out with a load of 3 mN in the same direction. Critical loads L_{C1} and L_{C2}, indicating the onset of cohesive and adhesive failure of the coatings, respectively, were determined using load vs. depth profiles in combination with optical and SEM (LEO 440, Zeiss, Germany).

Wear tests in a ball-on-disc equipment were conducted based on ASTM F 732-00 (2006). The samples were tested against a Si₃N₄-ball (6 mm in diameter, Spekuma, Sweden), to simulate the coating sliding against itself. The disc specimen was rotated at a speed of 0.04 m/s applying a normal load of 1 N, forming a wear track of 5 mm in diameter. Due to differences in wear performance, tests were run for 1 000 and 10 000 revolutions, for Si_xC_yN_z and Si_xN_y coatings, respectively. In order to simulate physiological conditions, the wear tests were run in a serum solution of 25% fetal bovine serum (Gibco, EU approved, origin South America) with sodium azide (Sigma-Aldrich, St Louis, USA) and ethylene-diaminetetraacetic acid (EDTA, Sigma-Aldrich, St Louis, USA) as specified in the standard ASTM F 732-00 (2006). The wear rate was quantified using the specific wear rate according to Archard's wear equation ([Archard, 1953](#)):

$$\text{Specific wear rate} = \frac{\text{Wear volume}}{\text{Load} \cdot \text{Sliding distance}} \quad . \quad (\text{Eq 1})$$

The wear rate, excluding the ball, was calculated from the worn cross-sectional area, measured with vertical scanning interferometry (VSI, Wyko NT-1100, Veeco, USA). VSI was also used to determine surface roughness (R_a).

3. Results

The relative C concentration was estimated using EDS, and was found to increase with increasing C-target power and decreasing power on the Si target, as shown in Table 1. The C concentration did not appear to be affected by the different deposition temperatures.

3.1. Hardness and elastic modulus

The hardness and elastic modulus are displayed in Fig. 1, and the hardness to elastic modulus ratio (H/E) is specified in Table 1. All coatings were found to be harder than CoCr but softer than bulk Si_3N_4 . Generally, the Si_xN_y coatings were harder than the $\text{Si}_x\text{C}_y\text{N}_z$ coatings. Very similar hardness values of the coatings were recorded on both substrates (Si or CoCr), Fig 1, confirming that there was no influence from the substrate in the hardness and elastic modulus measurements.

3.2. Micro scratching

The micro scratching revealed adhesive failure for the Si_xN_y coatings at loads above 214 mN, and coatings SiN (3/-/l), (4/-/l), and (3/-/h) resisted loads up to the maximum 300 mN without any rupture, see Table 1. The adhesive failure of Si_xN_y coatings occurred by extensive flaking in front of and behind the scratching tip, Fig. 2a and b. The deformation and redistribution of the material before failure for all Si_xN_y coatings, except SiN (1/-/l), was accompanied by the formation of micro cracks on the ridges, Fig. 2a. The SiN (1/-/l) coating deformed without visible micro cracking up to final failure, Fig. 2b. Cohesive failure of the $\text{Si}_x\text{C}_y\text{N}_z$ coatings occurred at loads around 50 mN and adhesive failure below 105 mN. Coatings deposited with higher Si target power (4 kW) showed cohesive failure by flaking (Fig. 2c), while coatings deposited at the lower target power (1 kW) showed cohesive failure by transverse cracks (Fig. 2d), both followed by adhesive failure of the coating. $\text{Si}_x\text{C}_y\text{N}_z$

coatings deposited on CoCr showed half the cohesive and adhesive failure loads of those deposited on Si-wafers.

3.3. Friction and wear

The Si_xN_y coatings showed a stable friction coefficient between 0.2 and 0.3 over 10 000 revolutions, see Fig. 3. An exception was SiN (4/-/I), which had a drastic friction increase in the beginning and later reached a stable friction coefficient of 0.33. Both reference materials showed a lower friction coefficient than the Si_xN_y coatings. Cross-section profiles of the wear tracks on the Si_xN_y coating, sintered Si_3N_4 and CoCr, from which the wear rates were calculated, are demonstrated in Fig. 4. The SiN (4/-/I) coating wore down to a depth of 2 μm and is not shown in the figure. With respect to CoCr, the Si_xN_y coatings, except SiN (4/-/I), showed a much higher wear resistance, similar to that of Si_3N_4 . Examples of the wear tracks are displayed in Fig. 5 and specific wear rates are given in Table 1. The Si_xC_yN_z coatings were tested for 1 000 revolutions in the ball-on-disc tests, as previously mentioned. The majority of these coatings were worn through and failed during the test. The lowest wear rate of the Si_xC_yN_z coatings was $100 \times 10^{-7} \text{ mm}^3/\text{N m}$, obtained for SiCN (1/1.4/I).

4. Discussion

In this study, Si_xN_y and Si_xC_yN_z coatings were produced using HiPIMS and evaluated in terms of mechanical properties using nanoindentation (for hardness and elastic modulus), micro scratching (for cohesive and adhesive properties), and in a ball-on-disc setup (for friction and wear properties). The amount of C in the coatings was analyzed by EDS. However, these C concentrations should be interpreted as relative concentrations within this study, rather than absolute quantitative values. This caution is necessary since no standard was used for calibration of the measurements, and EDS has limitations in detecting light elements. Despite this, the values presented can be used for relative comparisons within the study and the C concentrations correlate well with what was expected from the deposition rates from the targets.

An electron flight simulation based on a Monte Carlo model was performed assuming an acceleration voltage of 5 kV in Si_3N_4 and estimated the maximum information depth to 0.3 μm . Also, the absence of Co, Cr and Mo signals in the EDS analysis of coatings deposited on CoCr, confirms that the chemical information was obtained from the coating only.

For hip joints there is a risk that wear particles or bone cement particles become trapped in the contact and cause abrasion ([Bragdon et al., 2003](#); [Dowling et al., 1978](#) ; [Wang and Essner, 2001](#)). A higher hardness of the joint bearing surfaces could therefore be an advantage by increasing the resistance to two and three body abrasive wear. The Si_xN_y coatings were found to possess a high hardness, up to 21 GPa, while the hardness of some of the Si_xC_yN_z coatings were half of that. These variation are likely caused by the chemical and microstructural differences between the two types of coatings, caused by the C content and the layered structure (from the sample rotation, see section 2.1) of the Si_xC_yN_z coatings. The hardness and elastic modulus of the Si_xN_y and Si_xC_yN_z coatings (especially for coatings with a low C content) was similar to literature data for coatings deposited using different sputtering methods (DC, r.f. and HiPIMS) ([Olofsson et al., 2012](#); [Pusch et al., 2011](#); [Shi et al., 2012](#)). For the Si_xN_y coatings, a lower Si target power resulted in harder coatings, while no dependence of the deposition temperature was evident. The relation is probably linked to chemical differences between the Si_xN_y coatings. These trends did not apply to the Si_xC_yN_z coatings. The reason for a lower hardness and elastic modulus for SiCN (1/0.7-1.4/l) is not yet fully understood. The difference in deposition temperature possibly affects the morphology, microstructure and/or chemistry in the coating and will be further investigated in a follow up study. The elastic moduli of the majority of the coatings were similar to that of CoCr, except SiCN (1/0.7-1.4/l), as discussed above.

The coatings differed in thickness, consequently the failure loads (L_{c1} and L_{c2}) were not compared. However, the modes of failure in micro scratching were found to correlate with the wear properties. For the Si_xN_y coatings, the wear resistance appeared to relate to the ability to avoid micro cracks before adhesive failure. The SEM analysis showed that no micro cracks were formed before failure for SiN (1/-/l) in Fig. 2b, (compare with Fig. 2a). This coating also showed the highest hardness, i.e. the

best ability to resist plastic deformation. A more brittle fracture can be seen for the harder SiN coatings in Fig. 2a and b, compared to the more ductile behavior seen for SiCN coatings in Fig. 2c and d. SiN (1/-/l) also showed the lowest wear rates and the highest H/E ratio. Leyland described the H/E ratio as a better way of predicting wear performance than hardness or elastic modulus individually ([Leyland and Matthews, 2000](#)). This approach predicts the poor wear performance for CoCr, but shows no trend for the remaining samples. The cohesive failure types for $\text{Si}_x\text{C}_y\text{N}_z$ coatings, cracks and flakes, are believed to be related to different microstructures of the coatings, caused by deposition at different Si target powers. A higher Si target power is hypothesized to give a laminar structure and a lower power a columnar structure, since failure of a laminar structure appears between the lamellas, whereas for a columnar structure the failure arises between the columns. This may be a drawback for the $\text{Si}_x\text{C}_y\text{N}_z$ coating, since weaker parts in the coatings risk a non-homogenously distributed failure through the coating, which can be hard to predict. When coatings were deposited on CoCr, the failure loads were only half of those on Si-wafers, which indicates that further optimization of the coating adhesion to CoCr is possible.

It is not yet completely understood why coating SiN (4/-/l) differs from the remaining Si_xN_y coatings in the wear test. The high wear rate is most likely related to the initially higher friction and possibly also the lower hardness, causing a larger contact area in the wear test. Neither could the low wear resistance of $\text{Si}_x\text{C}_y\text{N}_z$ coatings be fully explained. Coatings SiN (1 to 3/-/l) and (2 to 3/-/h) displayed notably lower wear rates than the other coatings. The rates were close to Si_3N_4 -on- Si_3N_4 . In comparison with similar studies, the Si_xN_y coatings matched the wear rates of Si_3N_4 -TiN-composite-on- Al_2O_3 ([Mazzocchi et al., 2008](#)), CrN-on-CrN and CrCN-on-CrCN, and performed better than TiN-on-TiN and CoCr-on-CoCr ([Williams et al., 2003](#)), and were also superior to most CoCr-on-UHMWPE (([Saikko et al., 2001](#)), summary table p. 512). In relation to r.f. sputtered Si_xN_y coatings in a study by ([Olofsson et al., 2012](#)), the wear rates with the HiPIMS deposited Si_xN_y coatings had similar to slightly lower wear rates, although the friction were somewhat higher in this study. Coatings deposited at lower Si target power had a slightly lower wear rate, these coatings also show the highest hardness, as discussed. Note that additional parameters to those in Eq. 1 can affect the wear (for

example surface roughness), therefore caution needs to be taken when making direct comparisons with other studies. Future work should focus on understanding not only the wear but also the wear particles, since dissolution of wear particles may reduce a possible negative body response. The amount, size, shape, composition, bonding structure of the particles as well as pH etc. could affect the dissolution rate. The dissolution rate needs to be tuned so that the wear particles can dissolve but not the coating to a high extent.

The test configuration with a ceramic ball sliding against the various coatings was used in order to simulate Si_xN_y or $\text{Si}_x\text{C}_y\text{N}_z$ coatings wearing against themselves. The most common *in vivo* configuration for CoCr is towards UHMWPE, where the majority of material loss occurs on the polymer. This is in contrast to the tested configuration Si_3N_4 -on-CoCr, where mainly the CoCr was worn. However, the model test can relate the coatings wear resistance in to Si_3N_4 -on- Si_3N_4 and Si_3N_4 -on-CoCr.

An initial study of using Si_xN_y and $\text{Si}_x\text{C}_y\text{N}_z$ for joint replacements was performed, motivated by previous DFT calculations. However, further development and investigations are needed. Wear studies were made in model tests comparing the coatings among each other and in relation to present materials for the specific application, future wear tests should include hip or knee simulator studies. In order to approach the application, an understanding of the structure and chemistry of the coatings has to be acquired along with the biological response both to the coating, wear particles, and the lubrication around the implant. As for the bearing surface of joint replacements a thickness of tenths of micrometers is needed, for this, excellent coating adhesion is required and needs, thus further investigations. Nevertheless, this initial promising result motivates further work on Si_xN_y and $\text{Si}_x\text{C}_y\text{N}_z$ for joint replacements.

5. Conclusions

Si_xN_y and $\text{Si}_x\text{C}_y\text{N}_z$ coatings have been deposited using HiPIMS in order to explore a wear resistant alternative for bearing surfaces in total joint replacements. The coatings showed hardness ranging

from that of sintered Si_3N_4 to CoCr. The elastic modulus of the majority of Si_xN_y and $\text{Si}_x\text{C}_y\text{N}_z$ coatings were similar to that of CoCr. The wear resistance of all of the Si_xN_y coatings except one was in a range similar to that of sintered Si_3N_4 and significantly higher than that of CoCr. This promising mechanical property may be explained by the coating's ability to avoid cohesive cracks. None of the $\text{Si}_x\text{C}_y\text{N}_z$ coatings showed wear resistance matching that of Si_3N_4 or the Si_xN_y coatings under the tested conditions. Also, there is room for process optimization to increase the adhesion to CoCr substrates.

In conclusion, Si_xN_y coatings are of great interest for further studies because of their combination of hardness, elastic modulus, and wear resistance. In particular the SiN (1/-/I) coating, which exhibited the highest hardness (21 GPa), one of the higher elastic moduli (212 GPa), the lowest wear rate ($1.3 \cdot 10^{-7} \text{ mm}^3/\text{Nm}$) and also fractured in a homogenous way in the scratch test.

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Table 1 - Deposition parameters and summary of test results for Si_xN_y and $\text{Si}_x\text{C}_y\text{N}_z$ coatings on silicon wafers and CoCr (marked '*'). The high (h) and low (l) substrate temperature corresponds to approx. 430 °C and 110 °C, respectively. Coatings that failed in the wear test are marked (f).

Coating Name (Si-target power [kW]/ C-target power [kW]/Temp.)	C content by EDS [at. %]	H/E ratio	Cohesive failure (L_{C1}) ± SD [mN]	Adhesive failure (L_{C2}) ± SD [mN]	Specific wear rate (1 N, n=1 000) [mm ³ /N m]	Specific wear rate (1 N, n=10 000) [mm ³ /N m]
SiN (1/-/l)	1	0.100	-	214 ± 12	n/a	$1.3 \cdot 10^{-7}$
SiN (2/-/l)	2	0.087	-	260 ± 15	n/a	$2.2 \cdot 10^{-7}$
SiN (3/-/l)	1	0.086	-	no rupture	n/a	$2.3 \cdot 10^{-7}$
SiN (4/-/l)	0	0.086	-	no rupture	n/a	$240 \cdot 10^{-7}$
SiN (2/-/h)	1	0.093	-	265 ± 8	n/a	$2.1 \cdot 10^{-7}$
SiN (3/-/h)	1	0.091	-	no rupture	n/a	$4.8 \cdot 10^{-7}$
SiCN (4/0.5/l)	6	0.081	68 ± 6	85 ± 5	f	n/a
SiCN (4/0.5/l)*	8	0.075	26 ± 2	36 ± 5	n/a	n/a
SiCN (4/0.7/l)	9	0.078	55 ± 2	81 ± 7	f	n/a
SiCN (4/0.7/l)*	9	0.080	20 ± 3	33 ± 4	n/a	n/a
SiCN (4/1.4/l)	14	0.083	65 ± 7	83 ± 8	f	n/a
SiCN (1/0.7/l)	23	0.072	39 ± 6	46 ± 3	$130 \cdot 10^{-7}$	n/a
SiCN (1/1.0/l)	30	0.074	42 ± 2	52 ± 8	$410 \cdot 10^{-7}$	n/a
SiCN (1/1.4/l)	35	0.072	36 ± 2	42 ± 1	$100 \cdot 10^{-7}$	n/a
SiCN (4/0.5/h)	6	0.088	68 ± 6	80 ± 4	f	n/a
SiCN (4/0.5/h)*	8	0.078	35 ± 3	67 ± 5	n/a	n/a
SiCN (4/0.7/h)	9	0.084	77 ± 3	95 ± 5	f	n/a
SiCN (4/1.4/h)	15	0.089	68 ± 5	86 ± 2	f	n/a
SiCN (1/0.7/h)	22	0.080	86 ± 9	105 ± 15	f	n/a
SiCN (1/1.0/h)	29	0.079	62 ± 4	76 ± 2	$110 \cdot 10^{-7}$	n/a
Si ₃ N ₄	n/a	0.035	n/a	n/a	n/a	$1.0 \cdot 10^{-7}$
CoCr	n/a	0.078	n/a	n/a	n/a	$60 \cdot 10^{-7}$

Fig. 1 - Hardness and elastic modulus with indicate standard deviation for Si_xN_y and $\text{Si}_x\text{C}_y\text{N}_z$ coatings on Si wafers and on CoCr (marked ‘*’) as well as the two reference bulk materials, CoCr and Si_3N_4 .

Fig. 2 - Scratch test of coatings deposited on silicon wafers for a) Si_xN_y coating SiN (2/-/h), b) Si_xN_y coating SiN (1/-/l), c) $\text{Si}_x\text{C}_y\text{N}_z$ coating SiCN (4/1.4/l), deposited with a Si-target power of 4 kW, and d) $\text{Si}_x\text{C}_y\text{N}_z$ coating SiCN (1/1.0/l), deposited at 1 kW. The arrow indicates the direction of scratching.

Fig. 3 - Friction coefficient versus number of revolutions from ball-on-disc test for tests run 10 000 cycles for Si_xN_y coatings and the reference materials.

Fig. 4 - Wear track cross-section profiles for all Si_xN_y coatings, except SiN (4/-/l) , plotted with CoCr and sintered Si_3N_4 as reference. Note the scale difference of the x and y axes.

Fig. 5 - Samples with wear tracks after 10 000 revolutions in ball-on-disc test. The sample size is 362 μm (width) $\times$ 452 μm (depth) $\times$ 3 μm (thickness).