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«Carbon-rich self-healing multifunctional nanostructured smart coatings (NSC) for high-tech applications using high-power confined plasma technology for their deposition»

Nanostructured Smart Coatings

WP2 Carbon-rich Coating Testing

Deliverables – a new methodology for measuring and evaluating the characteristic of wear-resistant nanostructured coatings using selected surface texture (3D) parameters.

FLPP Project No. 2019/1-0385 "Carbon-rich self-healing multifunctional nanostructured smart coatings (NSC) for high-tech applications using high-power confined plasma technology for their deposition"

METHODOLOGY FOR MEASURING AND EVALUATING THE CHARACTERISTICS OF NANOSTRUCTURED COATINGS USING SELECTED SURFACE TEXTURE PARAMETERS

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The methodology is intended for Nanostructured Superlattice Coatings (NSC) deposited by advanced Physical Vapour Deposition (PVD) technique tribological characteristics (Friction and Wear) measuring and evaluating with respect to surface texture 3D parameters.

This document is recommended for use within the following measurement limits:

- NSC thickness 2000 – 6000 nm.
- Steady-state friction coefficient 0.1 – 0.9, standard deviation <0.1.
- Specific wear rate $1 \times 10^{-8} – 1 \times 10^{-5}$, the depth of the wear < NSC thickness.

1. GENERAL TERMS

1.1. The measurement and evaluating methodology regulates the measurement methods used, requirements for measuring instruments, auxiliary devices, materials, requirements for the qualification of operators and safety requirements, requirements for measurement conditions and measurement procedures, processing of measurement results and accuracy control, and requirements for measurement accuracy.

1.2. The document has been created taking into account the guidelines of the standards ISO 10012:2003, ISO 5725-1:1994, ISO 5725-4:2020, ISO 9000:2015, ISO guide 99:2007.

2. MEASUREMENT METHODS

The developed methodology determines the following measurement methods:

2.1. Quantitative measurement method is used to collect experimental data.

2.2. Statistical methods are used in data processing: descriptive statistics.

2.3. The relevance between surface texture parameters and tribology characteristics is characterized by correlation analysis.

3. REQUIREMENTS FOR MEASURING INSTRUMENTS, AUXILIARY DEVICES, MATERIALS

3.1. Ambient climate and instruments for measuring the ambient climate.

Ambient conditions recommended in the standards ISO 18535:2016 and ISO 1:2022 must be ensured in the room intended for measurements. Ambient measuring instruments must measure the ambient temperature and relative humidity in the range determined by ISO 18535-2016 and ISO 1:2022. Can be used, for example, P330 Temp (Dostmann, Germany) or analog.

3.2. Equipment for tribology measurements.

Friction and wear measurements are performed with a ball-on-disc tribometer, following the recommendations of the standard ISO 18535:2016. For example, TRB3 (CSM Instruments, Needham Heights, MA, USA) or analog can be used. 100Cr6 (ISO 683-17:2015) steel ball (Ø6 mm) or analog.

A 2D profilometer can be used to determine the cross-sectional area of the worn surface. For example, Surftest SJ-500 (Mitutoyo, Japan) and MCubeMap Ultimate 8.0 to calculate cross-sectional area or analog can be used.

3.3. Equipment for surface texture measurements.

Surface texture measurements are performed with a 3D profilometer, following the recommendations of the standards ISO 25178-601:2010 and ISO 25178-3:2012. For example, an AVANT (Mitutoyo, Japan) profilometer and standard stylus 12AAC731 or analog can be used. For data post-processing, MCubeMap Ultimate 8.0 or analog can be used.

4. OPERATOR QUALIFICATION REQUIREMENTS AND SAFETY REQUIREMENTS

To perform and evaluate tribology tests, the operator must have advanced knowledge in the field of tribology science. Must be able to work correctly with a ball-on-disc tribometer and relevant software.

In order to perform and evaluate surface texture measurements, the operator must have advanced knowledge in the field of dimensional metrology science. Must know how to work with a 3D profilometer and relevant software properly.

Specific safety requirements are not regulated, but the guidelines given by the equipment manufacturers must be followed.

5. PREPARATION FOR MEASUREMENTS AND MEASUREMENT PROCEDURE

This methodology assumes that the NSC thickness is known. A Calo tester and optical microscope can be used to determine the thickness of the coatings with a thickness between 0.1 to 50 micrometers. The measurement procedure can be seen in Figure 1.

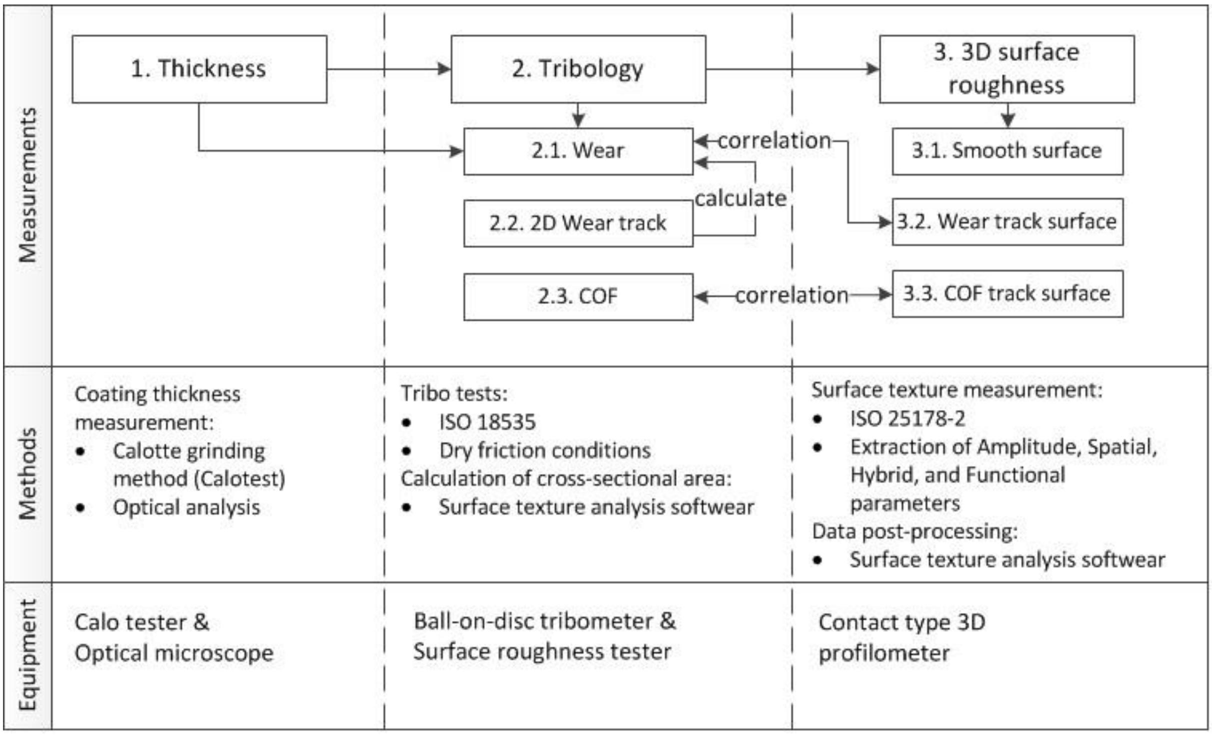

Fig.1. Measurement procedure for measuring and evaluating the surface texture and tribological properties of deposited NSC

5.1. Calibration of equipment and recording of ambient conditions.

Ambient conditions must be checked in the room where the measurements are performed. The ambient conditions must be in accordance with the ISO 18535:2016 standard recommendations in the case of tribology measurements or the ISO 1:2022 standard recommendations in the case of surface texture measurements. Suppose it is impossible to perform measurements according to the abovementioned standards' recommendations. In that case, the measurement uncertainty must be calculated according to, for example, document EA-4/02M:2022, or if the equipment software allows it, an automatic or manual correction must be made in the equipment software before measurements.

Before measuring, the device must be calibrated according to the manufacturer's guidelines, making sure that the device works correctly.

5.2. Tribology measurements.

Tribology measurements are performed under a dry friction regime. Treatment of specimen before test and test preparation according to ISO 18535:2016 standard, clause 7.1 and 7.2.

5.2.1. Wear test.

Testing conditions according to ISO 18535:2016 standard recommendations:

a) Applied load: 5 N;

b) Sliding speed: 0.1 m/s*;

c) Sliding distance: 1000 m.

The wear track must be measured at least in 4 positions at a constant angular distance using, for example, a 2D profilometer. From at least 4 profiles, the average worn cross-sectional area can be calculated using, for example, MCubeMap Ultimate 8.0 software. The average worn cross-sectional area can be used as a primary parameter to characterize the wear characteristics of a coating. The specific wear rate can be calculated further according to ISO 18535:2016, clause 8.2.1.

5.2.2. Friction coefficient test.

Testing conditions according to ISO 18535:2016 standard recommendations:

a) Applied load: 3 N;

b) Sliding speed: 0.05 m/s*;

c) Sliding distance: 100 m.

Initial, steady-state, maximum, and minimum friction coefficient values should be determined. Initial, maximum, and minimum friction coefficient values are recommended to be determined from the tribometer program, for example, Tribo X software, version 4.0. Steady-state friction coefficient values are recommended to be determined in a stable location (friction coefficient does not rise or fall rapidly) from the friction coefficient curve at least in a 10-20 m friction coefficient curve section and calculated as the average Steady-state friction coefficient. The friction coefficient test wear track cross-sectional area should be measured as in 5.2.1. If the wear track depth exceeds the thickness of the coating, then the dependence of the correlation with the surface texture parameters (5.3.) cannot be determined.

*- see ISO 18535:2016 clause 7.3.

Friction coefficient values shall be stated to two significant digits.

5.2.3. Test report should contain information described in ISO 18535:2016 clause 9.

5.3. Surface texture measurements.

Surface texture measurements must be performed with 3D contact or non-contact profilometer in the area that includes both smooth specimen surface and surface after friction coefficient test or wear test, depending on the outcome of interest.

The recommended surface texture measurement settings using AVANT (Mitutoyo, Japan) 3D profilometer with a 12AAC731 stylus (2 µm tip diameter) are described in Table 1.

Table 1. Surface roughness measurement settings

Stylus	*Standard Stylus Arm 12AAC731, tip radius 2 µm*	Analog is allowed.
Points (X;Y)	300 x 8000	A higher number of points is allowed.
Measured area (X;Y)	2 x 2 mm	A larger measurement area is allowed.
Measurement speed	0,5 mm/s	A slower measurement speed is allowed.

5.4. Post-processing.

The data can be post-processed with the software of an appropriate apparatus, e.g., MCubeMap Ultimate 8.0 or analog. Algorithm for surface texture data post-processing using Fast Fourier Transform (FFT) to segment 3D surface texture after the tribology test is presented in Fig. 2.

5.4.1. Algorithm using integrated FFT measurement approach.

5.4.1.1 Measured surface, according to 5.3, must include wear track and smooth surface parts.

5.4.1.2. If necessary obvious outliers should be removed.

5.4.1.3. Separately filter the roughness and waviness part for the smooth surface and the wear track, using an appropriate cut-off value based on the recommendations of standard ISO 25178-3.

5.4.1.4. Extract wear track area and smooth surface area.

From the filtered surface (5.4.3.), manually extract the wear track surface part and the smooth surface part. The extracted area varies from the wear track size but should be measured as large as possible to include more information about surface roughness.

5.4.1.5. Calculate surface texture parameters

Calculate surface texture parameters for the wear track and smooth surface part according to ISO 25178-2:2022.

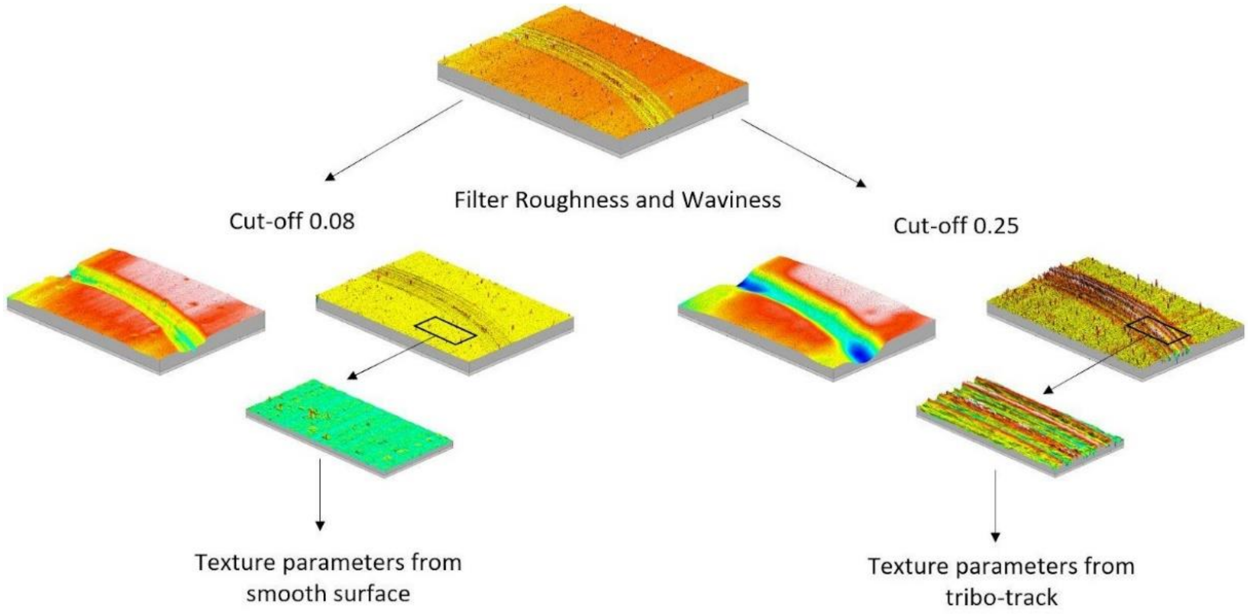

Fig. 2. Surface texture data post-processing [1].

6. MEASURED DATA EVALUATION

This methodology deals with data evaluation between friction coefficient (measured according to 5.2.2.), wear (measured according to 5.2.1.), and surface texture parameters (measured according to 5.3.). The wear track's depth must not exceed the coating's thickness after the friction coefficient test (5.2.2.).

6.1. Empirically obtained direct measurement results (wear cross-sectional area, steady-state friction coefficient) are processed as follows:

6.1.1. Of all performed n measurements, the arithmetic mean value is calculated:

$$\bar{x} = \frac{m_1 + m_2 \dots + m_n}{n}, \quad (1.1.)$$

where, $m_1, m_2 \dots m_n$ – measurements;
n – number of measurements performed.

6.1.2. Calculates the standard deviation of the measurements:

$$\sigma = \sqrt{\frac{(m_1 - \bar{x})^2 + (m_2 - \bar{x})^2 + \ldots + (m_n - \bar{x})^2}{n - 1}}. \quad (1.2.)$$

6.1.3. Calculates the error limits of the largest possible measurements:

$$\Delta_{lim} = \pm 3\sigma. \quad (1.3.)$$

Measurements that exceed the error limits may be considered grossly erroneous and are excluded.

6.1.4. Selects the value of the confidence probability β – 0,95 and, according to Table 2, find the value of the Student's coefficient $t_\beta(n)$. Tables of Student's coefficient values can be used.

Table 2. Excerpt from Student's Ratio Table $t_{\beta}(n)$

β / n	0,70	0,95	0,99
5	1,16	2,57	4,03
6	1,13	2,45	3,71
7	1,12	2,36	3,50
8	1,11	2,31	3,36
9	1,10	2,26	3,25
10	1,09	2,23	3,17
∞	1,04	1,96	2,58

6.1.5. Accordingly, the absolute error of the measurement is calculated:

$$\Delta x_s = \sigma t_{\beta}(n), \qquad (1.4.)$$

where, $t_{\beta}(n)$ – The value of the Student's coefficient depends on the number of measurements taken.

6.1.6. Calculates the part of the systematic error that determines the accuracy of the measuring instrument:

$$\Delta x_{\delta} = \frac{\delta x}{3} t_{\beta}(\infty), \qquad (1.5.)$$

where, δx – fundamental error of the measuring instrument for the measurement of the quantity x;

$t_{\beta}(\infty)$ – The value of the Student's coefficient corresponding to an infinite number of measurements.

6.1.7. The final absolute error Δx is assumed to be the more significant value of the absolute (1.4.) and systematic error (1.5.) values. If Δx_s and Δx_{δ} differ less than three times, then the final absolute error Δx is calculated according to the following formula:

$$\Delta x = \sqrt{(\Delta x_s)^2 + (\Delta x_{\delta})^2}. \qquad (1.6.)$$

6.1.8. Calculates the relative error ε:

$$\varepsilon = \frac{\Delta x}{x_{vid}} 100\%; \qquad (1.7.)$$

The value of the relative error should be evaluated with caution, considering that the numerical values of the measurements significantly influence it. The smaller the error, the more accurate the measurements.

6.2. Steady-state friction coefficient correlation dependence with surface texture parameters

There is a correlation dependence between the surface texture parameters measured in wear track surface area and the values of the steady-state friction coefficient (see example in Annex A); therefore, if the quality of application of one nano-coating is to be evaluated, the values of the surface texture parameters can be used. Table 3 shows the recommended groups of surface texture parameters and the parameters according to their correlation dependence with the steady-state friction coefficient. The primary group of parameters indicated a strong correlation and accordingly, the correlation was observed to be lower in descending order for the other groups of parameters. Surface texture parameters and relevant groups are organized according to the ISO 25178-2: 2022 standard.

Table 3. Recommended surface texture parameters for friction coefficient data evaluation

		Groups of surface texture parameters	Recommended surface texture parameters*
↓	Primary	Amplitude parameters	*Sa, Sq, Sz, Sp, Sv, Ssk*
	Secondary	Material ratio function and related parameters	*Sk, Vmp, Vm, Vmc*
	Thirdly	-	*Rsm, Sci*
	Not recommended	Spatial, Hybrid parameters	

6.3. Wear correlation dependence with surface texture parameters

There is a correlation dependence between the surface texture parameters measured in wear track surface area and the values of the wear cross-sectional area (see example in Annex B); therefore, if the quality of application of one nano-coating is to be evaluated, the values of the surface texture parameters can be used. Table 4 shows the recommended groups of surface texture parameters and the parameters according to their correlation dependence with the wear cross-sectional area. The primary group of parameters indicated a strong correlation and, accordingly, the correlation was observed to be lower in descending order for the other groups of parameters. Surface texture parameters and relevant groups are organized according to the ISO 25178-2: 2022 standard.

Table 4. Recommended surface texture parameters for wear data evaluation

		Groups of surface texture parameters	Recommended surface texture parameters*
↓	Primary	Material ratio function and related parameters	*Vvv, Vvc, Vmc, Vmp, Vm, Vv*
	Secondary	Amplitude parameters	*Sz, Sku, Sv*
	Thirdly	-	*Sa, Sq, Sp, Svk*
	Not recommended	Spatial, Hybrid parameters	

*

Sa – Arithmetic mean height;
Sq – Root mean square height;
Sz – Maximum height;
Sp – Maximum peak height;
Sv – Maximum pit depth;
Rsm – Mean profile spacing;
Ssk – Skewness;
Sku – Kurtosis;
Sk – Core height;
Svk – Reduced valley depth;
Vmp – Peak material volume;
Vm – Material volume;
Vmc – Core material volume;
Vvv – Dale void volume;

Vvc – Core void volume.

7. REQUIREMENTS FOR PRECISION OF MEASUREMENTS

7.1. The permissible error limits of experimental measurements at the β value of the probability of reliability - 0.95 are as follows:

- Wear cross-sectional area relative error < 25%;
- Steady-state friction coefficient relative error < 20%.

The specified relative errors are recommended at the measurement limits specified in the developed methodology – friction coefficient ~0.9 and wear cross-sectional area ~800 μm^2. If the data is analyzed at a low friction coefficient and low wear, it is recommended to reduce the permissible relative errors accordingly.

Annex A (informative) Steady-state friction coefficient correlation dependence with surface texture parameters

This appendix discusses the correlation coefficient between the surface texture parameters measured in the wear track part and the steady-state coefficient of friction. The texture parameters are measured and calculated according to 5.4.2. Friction test is performed accordingly 5.2.2.

As an example, two PVD processes with different friction properties are discussed (see Table A1). Three NSC samples are selected for each PVD process to evaluate steady-state friction coefficient correlation dependence with surface texture parameters.

Table A1. Used NSC sample description

PVD Process	Sample Label	Coating's laminated structure	Thickness, (nm)	Steady-state friction coefficient
NSC 1	NSC 1.1; NSC 1.2; NSC 1.3	{TiWZr-CN/TiAlSi-N}$_{270}$|Ti|Substrate	~6500	NSC 1.1 – 0.17; NSC 1.2 – 0.20; NSC 1.3 – 0.16
NSC 2	NSC 2.1; NSC 2.2; NSC 2.3	{TiCrNb-CN/TiAlSi-N}$_{300}$|Ti|Substrate	~5200	NSC 2.1 – 0.72; NSC 2.2 – 0.78; NSC 2.3 – 0.64

The correlation is determined using a correlation coefficient. An example of how the correlation coefficient is determined for each NSC sample is shown in Figure A1 [1]. The example uses the correlation of the surface texture parameter Sa for three samples with a steady-state friction coefficient of NSC 1.

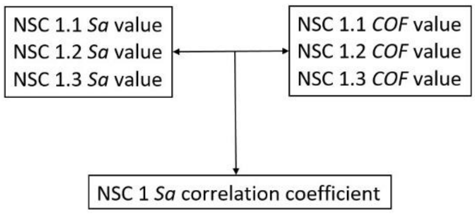

Figure A1. Example of correlation coefficient calculation. Three theoretically identical samples (NSC 1.1, NSC 1.2, and NSC 1.3) represent each PVD process (NSC 1) [1].

The measured surface texture parameters are compiled in Table A1.

Table A2. Surface Texture measurements (wear track part).

Parameter	NSC 1			NSC 2		
	NSC 1.1	NSC 1.2	NSC 1.3	NSC 2.1	NSC 2.2	NSC 2.3
Sa (nm)	84	102	70	80	251	96
Sq (nm)	100	117	82	99	326	124
Sp (nm)	221	262	156	241	1114	359
Sv (nm)	254	325	143	255	1860	260
Ssk	-0.6	-0.6	0.0	-0.1	-1.3	1.2

Sku	2.7	2.0	2.0	2.8	5.9	3.8
Sz (nm)	460	500	297	493	2600	620
RSm (mm)	0.009	0.016	0.015	0.014	0.020	0.013
RSm/Sa	107	157	214	174	80	136
Sq/Sa	1.2	1.1	1.2	1.2	1.3	1.3
Sp/Sz	0.5	0.5	0.5	0.5	0.4	0.6
Sds (pks/mm2)	5526	10,559	4409	10,682	5898	6870
Str	0.04	0.08	0.03	0.04	0.04	0.04
Sal (mm)	4.57×10^{-4}	7.39×10^{-4}	3.25×10^{-4}	5.53×10^{-4}	4.73×10^{-4}	3.59×10^{-1}
Sfd	2.08	2.20	2.11	2.18	2.12	2.10
Sdq	0.03	0.03	0.02	0.05	0.09	0.04
Ssc (1/µm)	0.29	0.23	0.22	0.22	0.38	0.36
Sdr (%)	0.05	0.03	0.03	0.12	0.42	0.08
Sk (nm)	226	204	127	218	443	171
Spk	72	128	119	82	145	232
Svk	63	31	48	93	599	95
Sr1	17.2	21.6	17.9	10.1	5.4	18.9
Vv	2.21×10^{-7}	2.01×10^{-7}	1.56×10^{-7}	2.41×10^{-4}	8.05×10^{-4}	3.60×10^{-4}
Vm	2.52×10^{-7}	3.24×10^{-7}	1.41×10^{-7}	2.54×10^{-4}	1.86×10^{-3}	2.57×10^{-4}
Vmp	3.67×10^{-8}	4.70×10^{-8}	2.52×10^{-8}	4.10×10^{-5}	2.23×10^{-4}	5.02×10^{-5}
Vmc	1.96×10^{-7}	2.51×10^{-7}	1.10×10^{-7}	1.90×10^{-4}	1.35×10^{-3}	1.79×10^{-4}
Vvc	1.01×10^{-7}	1.16×10^{-7}	1.03×10^{-7}	1.15×10^{-4}	3.04×10^{-4}	2.02×10^{-4}
Vvv	1.30×10^{-8}	9.91×10^{-9}	7.86×10^{-9}	1.12×10^{-5}	4.98×10^{-5}	7.04×10^{-6}
Spk/Sk	0.32	0.63	0.94	0.38	0.33	1.36
Svk/Sk	0.28	0.15	0.38	0.43	1.35	0.56
Spk/Svk	1.15	4.08	2.48	0.88	0.24	2.44

Calculated correlation coefficients between steady-state friction coefficient and surface texture parameters for both PVD processes are represented in Figure A2 (Only the top 10 correlation coefficients are shown in the figure for representation purposes). Other parameters showing promising correlation trends are *St*, *RSm*, *RSm/Sa*, *Sci* accordingly.

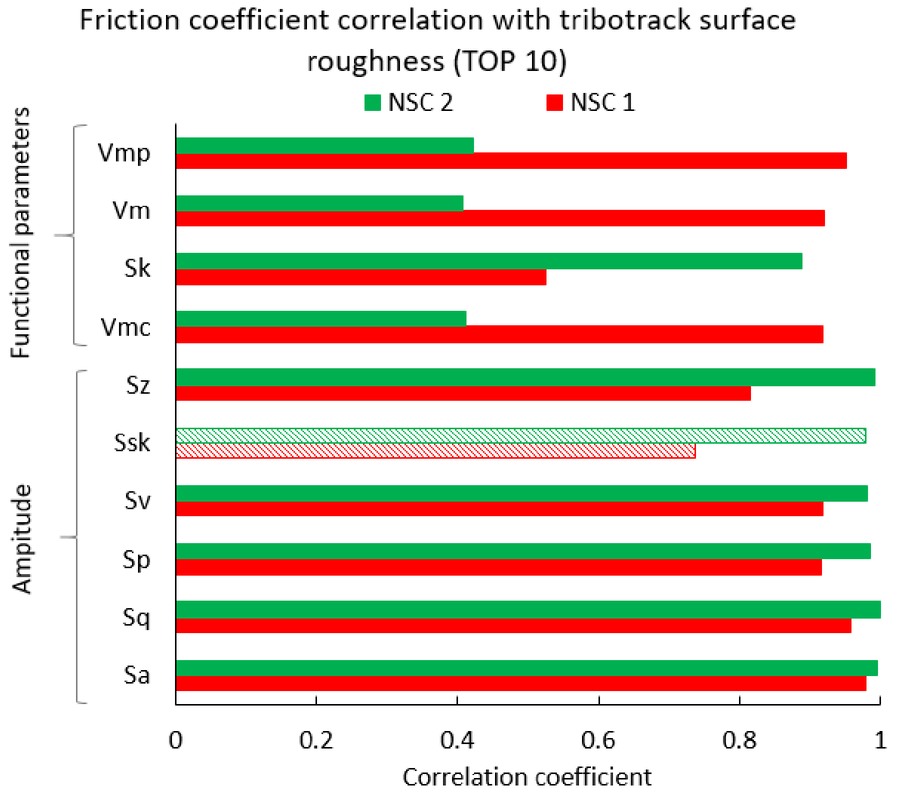

Figure A2. Friction coefficient correlation with wear track surface roughness parameters (TOP 10). NSC 1—red, NSC 2—green. Filled bars—positive correlation, strikethrough—negative.

Annex B (informative) Wear correlation dependence with surface texture parameters

This appendix discusses the correlation coefficient between the surface texture parameters measured in the wear track part and in this example, the wear cross-sectional area. The texture parameters are measured and calculated according to 5.4.2. A wear test is performed, and the cross-sectional area is calculated accordingly 5.2.1.

As an example, two PVD processes with different friction properties are discussed (see Table B1). Three NSC samples are selected for each PVD process to evaluate wear cross-sectional area correlation dependence with surface texture parameters.

Table B1. Used NSC sample description

PVD Process	Sample Label	Coating's laminated structure	Thickness, (nm)	Wear cross-sectional area, μm^2
NSC 1	NSC 1.1; NSC 1.2; NSC 1.3	{TiCrNb-CN/TiAlSi-N}$_{300}$ǀTiǀSubstrate	~5200	NSC 1.1 – 448; NSC 1.2 – 615; NSC 1.3 – 519
NSC 2	NSC 2.1; NSC 2.2; NSC 2.3	{Si-CN/Cr-N}$_{230}$ǀTiǀSubstrate	~5500	NSC 2.1 – 3128; NSC 2.2 – 3650; NSC 2.3 – 2583

The correlation is determined using a correlation coefficient. An example of how the correlation coefficient is determined for each NSC sample is shown in Figure A1.

The measured surface texture parameters are compiled in Table B2.

Table B2. Surface Texture measurements (wear track part).

Parameter	**NSC 1**			**NSC 2**		
	NSC 1.1	NSC 1.2	NSC 1.3	NSC 2.1	NSC 2.2	NSC 2.3
Sa (nm)	80	251	96	64	77	40
Sq (nm)	99	326	124	87	108	54
Sp (nm)	241	1114	359	256	351	188
Sv (nm)	255	1860	260	345	482	252
Ssk	-0.1	-1.3	1.2	-0.4	-0.6	0.3
Sku	2.8	5.9	3.8	4.7	5.1	4.9
Sz (nm)	493	2600	620	600	813	424
RSm (mm)	0.014	0.020	0.013	0.011	0.011	0.009
RSm/Sa	174	80	136	171	143	227
Sq/Sa	1.2	1.3	1.3	1.4	1.4	1.4
Sp/Sz	0.5	0.4	0.6	0.4	0.4	0.4
Sds (pks/mm2)	10,682	5898	6870	9623	8486	8616

Str	0.04	0.04	0.04	0.04	0.04	0.15
Sal (mm)	5.53×10^{-4}	4.73×10^{-4}	3.59×10^{-1}	1.75×10^{-4}	2.82×10^{-4}	3.20×10^{-4}
Sfd	2.18	2.12	2.10	2.15	2.16	2.16
Sdq	0.05	0.09	0.04	0.06	0.06	0.03
Ssc (1/µm)	0.22	0.38	0.36	0.31	0.23	0.14
Sdr (%)	0.12	0.42	0.08	0.16	0.16	0.06
Sk (nm)	218	443	171	227	222	101
Spk	82	145	232	76	117	65
Svk	93	599	95	122	196	59
Sr1	10.1	5.4	18.9	7.0	9.9	8.7
Vv	2.41×10^{-4}	8.05×10^{-4}	3.60×10^{-4}	2.57×10^{-7}	3.51×10^{-4}	1.88×10^{-4}
Vm	2.54×10^{-4}	1.86×10^{-3}	2.57×10^{-4}	3.43×10^{-7}	4.80×10^{-4}	2.49×10^{-4}
Vmp	4.10×10^{-5}	2.23×10^{-4}	5.02×10^{-5}	4.69×10^{-8}	6.38×10^{-5}	3.22×10^{-5}
Vmc	1.90×10^{-4}	1.35×10^{-3}	1.79×10^{-4}	2.52×10^{-7}	3.51×10^{-4}	1.81×10^{-4}
Vvc	1.15×10^{-4}	3.04×10^{-4}	2.02×10^{-4}	8.91×10^{-8}	1.01×10^{-4}	5.41×10^{-5}
Vvv	1.12×10^{-5}	4.98×10^{-5}	7.04×10^{-6}	1.32×10^{-8}	1.82×10^{-5}	6.76×10^{-6}
Spk/Sk	0.38	0.33	1.36	0.33	0.53	0.64
Svk/Sk	0.43	1.35	0.56	0.54	0.88	0.59
Spk/Svk	0.88	0.24	2.44	0.62	0.60	1.10

Calculated correlation coefficients between wear cross-sectional area and surface texture parameters for both PVD processes are represented in Figure B1 (Only the top 10 correlation coefficients are shown in the figure for representation purposes). Other parameters that also showed promising correlation trends are *Sa, Sq, Sp, St, Svk, Sci, Svi.*

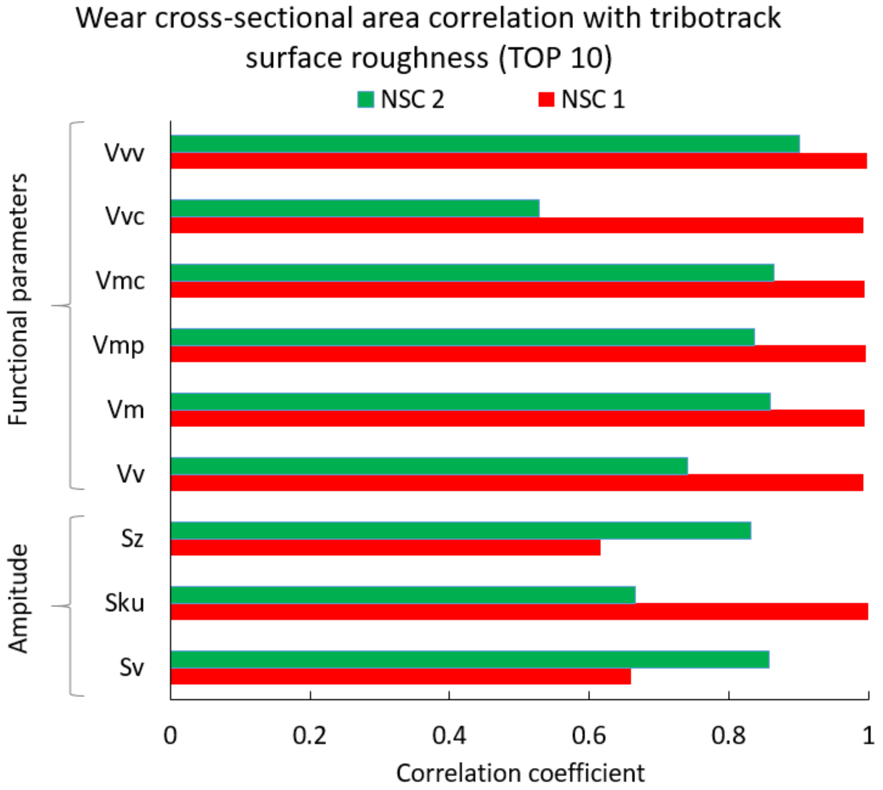

Figure B1. Wear cross-sectional area correlation with wear track surface roughness parameters (TOP 10). NSC 1—red, NSC 2—green. Filled bars—positive correlation, strikethrough—negative.

Annex C (informative) NSC life time calculation example

This appendix discusses an example where the wear rate is calculated for an NSC sample with following properties.

The measured surface texture parameters (ISO 25178-2: 2022) according to 5.*3 Surface texture measurements* in wear track area are:

Sa – 0.11 µm;

RSm_1 (Mean profile spacing perpendicular to the direction of friction) – 0.54 mm;

RSm_2 (Mean profile spacing parallel to the direction of friction) – 0.12 mm;

Str – 0.45.

The Physical – mechanical parameters used in this calculation example are:

µ (Poisson's ratio) – 0.3;

E (Elasticity module) – $2.2 \cdot 10^5$;

f (Friction coefficient, measured according 5.2.2.) – 0.1;

H (Surface microhardness) – 2200 MPa.

Fatigue characteristics used in this calculation example are [2]:

σ_0 (ultimate tensile strength) – 6000 MPa;

t (degree index of the fatigue curve equation for the material) – 3.

Dimensional characteristics measured and calculated from wear track:

$$q_a = \frac{F}{Aa} \tag{1.1.}$$

where,

F – Applied load, N;

Aa – Nominal area, mm^2.

The max linear wear (measured according 5.2.1), based on coating thickness:

h_{max} – 0.005 mm.

Firstly, to determine type of deformation (plastic or elastic) contact type criteria can be used. If contact type criteria value is ≥ 5, the deformation of material is elastic, but if value is ≤ 3 - contact is plastic [3–5]:

$$CC = \frac{RSm_1 \cdot (1-\mu^2) \cdot H}{E \cdot Sa} = \frac{54 \cdot (1-0{,}3^2) \cdot 2200}{0{,}11 \cdot 2{,}2 \cdot 10^5} = 4.47 \rightarrow elastic\ contact \tag{1.2.}$$

To calculate wear intensity combine formulas can be used [3,5]. For elastic contact:

$$I_h^{el} \approx \left(\frac{Sa}{Rsm_2}\right)^{t_{el}+1} \cdot \left(\frac{k_{\mu,f}}{\sigma_0 \cdot \theta}\right)^{t_{el}} \cdot F_3(\gamma)\frac{Ac}{Aa} \quad (1.3.)$$

For plastic contact:

$$I_h^{pl} \approx \left(\frac{Sa}{Rsm_2}\right)^{t_{pl}+1} \cdot \left(\frac{k_f}{e_0}\right)^{t_{pl}} \cdot F_3(\gamma)\frac{Ac}{Aa} \quad (1.4.)$$

where,

$$F_3(\gamma) = exp^{-\frac{\gamma^2}{2}} \cdot (4\gamma - \gamma^2)^{\frac{t}{2}} \cdot \left[\frac{exp^{-\frac{\gamma^2}{2}}}{\sqrt{2\pi}[1-\phi(\gamma)]} - \gamma\right] \quad (1.5.)$$

$$K_{\mu,f} = 4\sqrt{2\pi} \cdot f \cdot (1+\mu) \quad (1.6.)$$

$$K_f = 2\pi \cdot \sqrt{\frac{1+6f}{1-6f}} \quad (1.7.)$$

Ac – Contour area, mm^2.
where,

$$F_1(\gamma) = \left(\frac{q_a \cdot \theta}{k_{el}}\right) \cdot \left(\frac{Rsm}{Sa}\right) \quad (1.8.)$$

for elastic contact, and

$$F_2(\gamma) = \frac{q_a}{K_{pl} \cdot H} \quad (1.9.)$$

for plastic contact.

In the case of elastic contact (1.3. formula) and if $Ac \approx 0.1\ Aa$, wear intensity can be calculated:

$$I_h = \left(\frac{0{,}45 \cdot 0{,}11}{54}\right)^4 \cdot \left(\frac{1{,}3}{6000 \cdot 0{,}41 \cdot 10^5}\right)^3 \cdot 0{,}12 \cdot 0{,}1 \approx 1{,}15 \cdot 10^{-9}$$

Life time, if *W (constant sliding velocity)* – 0.12 m/min, can be calculated:

$$T = \frac{h_{max}}{I_h \cdot W} = \frac{5 \cdot 10^{-6}}{1{,}15 \cdot 10^{-9} \cdot 0{,}12 \cdot 60} \approx 6{,}04\ h \quad (1.10.)$$

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