

EVALUATION OF THE WEAR BEHAVIOR OF NITRIDE-BASED PVD COATINGS USING DIFFERENT MULTI-CRITERIA DECISION-MAKING METHODS

OCENA OBRABE NITRIDNEGA PVD NANOSA Z UPORABO RAZLIČNIH METOD VEČKRITERIJSKIH POSTOPKOV ODLOČANJA

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In this study, AISI 7131 (16MnCr5) case-hardened steel specimens were prepared in two groups, carbonitrided and without heat treatment, and the specimen surfaces were coated with three different coating materials (CrN, TiAlN and TiN) as a single layer using the physical vapor deposition (PVD) cathodic arc method. The wear behaviors of the coated specimens were tested with the micro-abrasion method. The test results of the micro-abrasion wear tests were analyzed with Multi-Criteria Decision Making (MCDM) techniques to determine the combination of coating and heat treatment that yields the lowest wear rate. According to the analyses conducted with the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Multiple Attribute Utility Theory (MAUT) and Compromise Programming (CP) MDCM techniques, the TiAlN coating exhibited the best wear performance. The MAUT and CP methods produced an identical ranking of the alternatives, whereas a slight deviation was found in the ranking with the TOPSIS method. Uncoated and CrN-coated specimens exhibited the worst wear performance of all the MCDM methods.

Keywords: wear, micro-abrasion, multi-criteria decision making, PVD coating

V študiji sta bili pripravljene dve skupini jekla za cementacijo AISI 7131 (16MnCr5), karbonitirana jekla in jekla brez toplotne obdelave, katerih površina vzorcev je bila prekrita s tremi različnimi nanosi (CrN, TiAlN in TiN) v enem sloju, s pomočjo fizikalne depozicije preko plinske faze (angl. PVD) z metodo obloka. Obnašanje vzorcev z nanosom pri obrabi je bilo preizkušeno z mikroabrazijsko metodo. Rezultati preizkusov mikroabrazijske obrabe so bili analizirani z uporabo večkriterijske tehnike odločanja (angl. MCDM), za določitev kombinacije nanos – toplotna obdelava, ki kaže najmanjšo hitrost obrabe. Glede na analize, ki so bile izvedene s pomočjo tehnike, ki je najbližja idealni rešitvi (angl. TOPSIS), s teorijo večkratne prednosti (angl. MAUT) in s programsko tehniko (angl. CP) MDCM-kompromisov, je najboljšo odpornost na obrabo pokazal TiAlN. MAUT- in CP-metodi dajeta enakovredne alternative, medtem ko je bilo manjše odstopanje ugotovljeno pri TOPSIS-metodi. Vzorci brez nanosa in s CrN nanosom so pokazali najslabšo odpornost na obrabo od vseh MCDM-metod.

Ključne besede: obraba, mikroabrazija, večkriterijsko odločanje, PVD-nanos

1 INTRODUCTION

Many of the machine parts used in automotive, aircraft and machine tools are exposed to mechanical loads under certain conditions in which they are in contact with their counterparts. Hence, many researches are conducted to understand the tribological properties of such parts to improve their service life and reduce the maintenance costs. One of the methods used to solve this problem is the thin-film coating application. In the thin-film coating process, the adhesive characteristics and hardness of the coatings are improved through optimization of the coating parameters using various deposition techniques.

In this work, the coatings (TiN, CrN and TiAlN) widely employed in actual industrial applications were selected and deposited by the cathodic arc-evaporation

PVD technique in order to make a comparative analysis of their tribological performances. In general, TiN and CrN coatings are known to be the most commonly employed thin hard coatings,^{1,2} whereas TiAlN is generally used for the coating of cutting tools in special machining operations.³

TiN, CrN and TiAlN thin hard coatings exhibit different wear behaviors due to their differing characteristic properties, such as friction coefficient, hardness, abrasive wear and corrosion resistance under various service conditions.^{3,4} Abrasive wear is one of the most commonly known wear mechanisms and it is of great importance in terms of the evaluation of the wear performance of coatings and the selection of abrasive wear-resistant coatings suitable for specific applications.⁵

The micro-abrasion wear-testing method is widely used to determine the abrasive wear resistance of thin

hard coatings.^{6–11} In the micro-abrasion wear test, the most effective test parameters that affect the test results can be classified as the rotational speed of the ball,^{12,13} the normal load,¹² the ball sliding distance,^{13–14} the ball surface condition¹⁵, the size^{6,16–19} and the type of abrasive particle in the slurry.²⁰

The coating materials may exhibit different wear performances depending on various test conditions. Therefore, it is necessary to determine the optimum test parameters that simulate the best service conditions. To select the most suitable material for a specific application, the criteria affecting the material selection should be properly identified.^{21,22} The selection of suitable thin hard coatings having the best wear performance among several choices for a specific application can be considered as a MCDM problem.^{23–24} The selection of the best method for a given problem is yet another important issue with no definite answer.²⁵ A. Abrishamchi et al.²⁶ state that the selection of an appropriate MCDM from a long list of available MCDM methods is a multi-criteria problem itself. There is no single MCDM technique that can be deemed superior for all decision-making problems.²⁷ TOPSIS, EXPROM2 (Preference Ranking Organization Method for Enrichment Evaluation), VIKOR (Višekriterijumsko Kompromisno Rangiranje – Multicriteria Optimization and Compromise Solution), ELECTRE (Elimination and Choice Expressing the Reality), Linear Assignment Method, and COPRAS (Complex Proportional Assessment)²⁴ are among the MCDM methods used by researchers for optimum selection among a variety of options in industrial problems.

A determination of the effects of the coating material and the nitriding processes on the wear behaviour of coating is a complex, multi-factorial problem and a limited number of studies are available in the literature on the use of MCDM techniques in the selection of coating materials. The TOPSIS method was used by A. Chauhan and R. Vaish²⁷ for the selection of the best alternative among hard coatings based on their hardness, Young's modulus, thermal expansion coefficient, H/E and H^3/E^2 ratios. H. Çalışkan et al.²⁴ used EXPROM2, TOPSIS and VIKOR methods to select the best coating material among a variety of multicomponent nanostructured boron-based hard coatings deposited using magnetron-sputtering and ion-implantation-assisted magnetron-sputtering methods in consideration of their hardness, Young's modulus, elastic recovery, friction coefficient, and critical load. Again, the EXPROM II, TOPSIS and VIKOR methods were used by H. Çalışkan et al.²⁴ to determine the best selection among a variety of materials for tool holders used in hard milling.

TOPSIS was developed by Hwang and Yoon (1981)²⁸ as a value-based compensatory method in conception and application,²⁹ which attempts to choose alternatives that are both closest to the positive-ideal solution and farthest from the negative-ideal solution.³⁰ The benefit criteria are maximized and the cost criteria are mini-

mized by a positive-ideal solution, and the opposite applies for the negative-ideal solution.³¹ TOPSIS provides a cardinal ranking of alternatives through the full use of the attribute information without a requirement for independent attribute preferences.^{32,33} The main strengths of the TOPSIS method can be listed as its understandable principle and easy implementation, its applicability, which requires a collection of precise and overall information,³⁴ a consideration of both positive and negative ideal solutions, the provision of a well-structured analytical framework for ranking of alternatives, and the use of fuzzy number to deal with alternatives.³⁵ The requirement of vector normalization for multidimensional problems can be regarded as a weakness of the method.

MAUT is a systematic method for the analysis and identification of multiple variables for obtaining a decision on a common basis.³⁶ In this method, a multi-attribute utility function is derived, which requires single utility functions and related weighting factors.^{37,38} For an evaluation of the performance criteria individually in the same units, single utility functions are used as a means to render their aggregation possible in the multi-attribute utility function. In this procedure an objective is set and attributes are established for the goal; a range of attributes are set; single utility functions are derived for each attribute; weighting factors are estimated for each attribute; and a multi-attribute utility function is derived.³⁹

The MAUT strategy allows the decision maker to make more objective decisions based on their experience and the result of the analysis.

The CP method was first developed by M. Zeleny⁴⁰ and later extended by A. Bárdossy, I. Bogárdi, L. Duckstein⁴¹ as composite programming for dealing with problems of a hierarchical nature. CP is within the class of distance-based, multi-criteria analytical methods, designed to identify non-dominated solutions, closest to an ideal solution by some distance measure.⁴² Its simple structure is one of the main advantages of this method. This is a simple and easily understandable method that provides good performance when compared with complicated and time-consuming methods.⁴³

In this study the micro-abrasion wear behaviour of single-layer CrN, TiN and TiAlN coatings was investigated using the fixed-ball micro-scale abrasion test. Afterwards, some of MCDM techniques such as TOPSIS, MAUT and CP, were implemented to compare their outputs as a means to determine the thin hard coating having the highest wear resistance. As indicated, there are studies^{23–24,28} available in the literature on the use of the TOPSIS method for the selection of the best alternative among a variety of coating applications. In this study the MAUT and CP methods are used to make a comparative analysis between TOPSIS and these methods. Also, among the other MCDM methods, the TOPSIS, MAUT and CP methods were chosen for their widespread usage,⁴⁴ easy computation and for being

within the same class of unique synthesis criterion approaches in which different points of view are merged into a unique functional structure for further optimization, which in turn facilitates the solution of material selection problems.⁴⁵

2 MATERIALS AND METHODS

2.1 Substrate and coating

Test samples made of AISI 7131 (16MnCr5) steel with a diameter of 40 mm and a thickness of 10 mm were used as a substrate for the deposition of TiN, TiAlN and CrN thin hard coatings. After the sample polishing process, all the test samples were subjected to a carburizing process performed in accordance with the heat treatment procedure given in **Figure 1**.

The substrate surface is hardened through a duplex surface treatment, a combination of nitriding and carburizing, since most of the applied forces must be supported by the substrate due to the thin structure of the PVD coatings.^{46–48} The nitriding process can provide a significantly high wear and adhesion resistance for TiAlN coatings.⁴⁹

Therefore, in this study, in addition to carburizing, a nitriding process was also applied to some samples to determine its synergistic effect on the abrasive wear behaviour of thin hard coatings. The nitriding process parameters are given in **Table 1**. The list of prepared samples is given in **Table 2**. After the carburizing and/or nitriding surface-hardening processes, polishing was performed as the last operation before the deposition process to remove the white layer (oxide or nitride layer) emerging during the heat treatment and having an adverse effect on the coating’s adhesion.⁵⁰ The average surface roughness of the polished samples was measured as $R_a = 0.02 \mu\text{m}$ after measurements conducted with a Mitutoyo SJ 201 profilometer. Before the coating process, the sample surfaces were washed 2 times with an alkaline detergent using an ultrasonic washing device. Then, the samples were washed 3 times with distilled

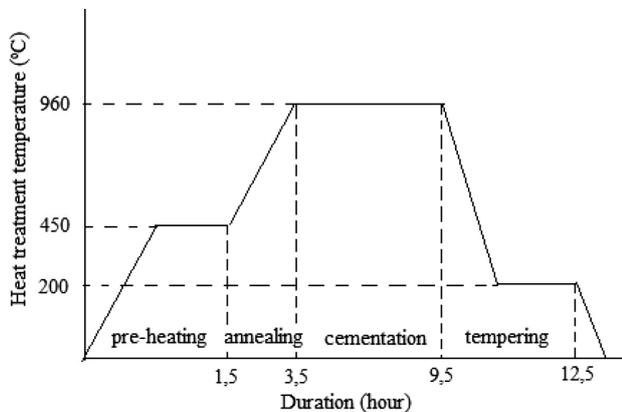


Figure 1: Process diagram of carburizing

Slika 1: Diagram poteka naogljčenja

water, each time for a period of 30 s, and then dried with hot air.

Table 1: Nitriding parameters

Tabela 1: Parametri nitiranja

Process type	Plasma nitriding
Temperature	480 °C
Duration	10 h
Gas mixture/ratio	Nitrogen-Hydrogen / 3:1
Pressure	2.5 mbar (in vacuum)

Table 2: Test sample classification

Tabela 2: Razvrstitev preizkusnih vzorcev

Coating material	Carburizing	Nitriding	Notation
CrN	+	-	CrN
CrN	+	+	CrN+N
TiN	+	-	TiN
TiN	+	+	TiN+N
TiAlN	+	-	TiAlN
TiAlN	+	+	TiAlN+N

Table 3: PVD deposition parameters

Tabela 3: Parametri PVD-depozicije

Parameter	Coating material		
	TiN	CrN	TiAlN
Cathode current	70 A	70 A	60 A
Bias voltage (DC)	50–60 V	50–60 V	50–60 V
Number of cathode	6	6	8
Duration	1 h	1 h 30 min	1 h 10 min

Following the ion bombardment on the coated sample surface, thin hard coatings were deposited on the sample surfaces using the parameters given in **Table 3** by the cathodic arc PVD technique.

2.2 Micro-abrasion test

The micro-abrasion wear test is a widely used method in the determination of the abrasive wear performance of thin hard coatings. In this study, micro-abrasion wear tests were carried out using a fixed-ball-cratering device shown in **Figure 2**. In micro-abrasion tests, an

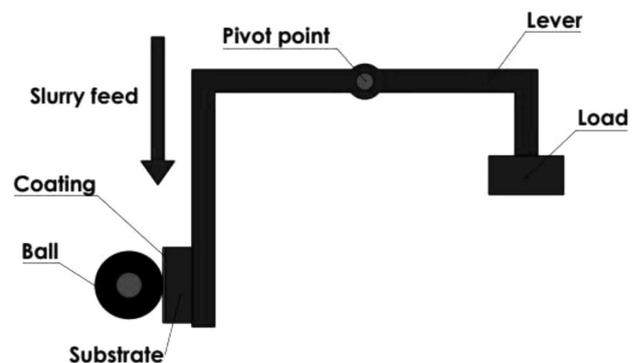


Figure 2: Scheme of the fixed-ball micro-abrasion test set up

Slika 2: Shema postavitve mikro-abrazijskega preizkusa s fiksno kroglo

abrasive slurry composed of 25 g of SiC in 75 mL distilled water for each abrasive mesh size (800, 1000 and 1200) mesh, was applied as 3 drops per minute, onto an AISI 52100 steel polished ball with a diameter of 25.4 mm.

2.3 Multi-criteria decision making method

2.3.1 Definition of the problem and setting up

Coating materials may yield differing wear results under different test conditions. In such situations a determination of the best choice for a coating material may be addressed as a multi-criteria decision making (MCDM) problem.^{23,24} In this study, implementation of MCDM methods is based on the assumption that each wear value obtained under different conditions is a criterion. The alternatives for the coating material are shown in **Table 4**.

Table 4: Alternatives for coating material
Tabela 4: Izbire materiala za nanašanje

Alternative	Material
A1	CrN
A2	N+CrN
A3	N+TiAlN
A4	N+TiN
A5	TiAlN
A6	TiN
A7	Uncoated

Table 5: Wear test factors

Tabela 5: Faktorji preizkusa obrabe

Abrasive (mesh)	Load (N)	Speed (r/min)
800	0,5	45
1000	1	90
1200	1,5	140

The factors for the wear test and their levels are shown in **Table 5**. 27 tests were conducted with these coating materials for three different factors. On the assumption that the wear rate found in each test is a criterion for a decision, our criteria can be organized as C(Abrasive, Load, Speed). Our criteria and the test parameters are shown in **Table 6**.

Table 6: Criteria parameters

Tabela 6: Merila parametrov

Criterion	Abrasive (mesh)	Load (N)	Speed (r/min)	Criterion	Abrasive (mesh)	Load (N)	Speed (r/min)	Criterion	Abrasive (mesh)	Load (N)	Speed (r/min)
C ₁	800	0.5	45	C ₁₀	1000	0.5	45	C ₁₉	1200	0.5	45
C ₂	800	0.5	90	C ₁₁	1000	0.5	90	C ₂₀	1200	0.5	90
C ₃	800	0.5	140	C ₁₂	1000	0.5	140	C ₂₁	1200	0.5	140
C ₄	800	1	45	C ₁₃	1000	1	45	C ₂₂	1200	1	45
C ₅	800	1	90	C ₁₄	1000	1	90	C ₂₃	1200	1	90
C ₆	800	1	140	C ₁₅	1000	1	140	C ₂₄	1200	1	140
C ₇	800	1.5	45	C ₁₆	1000	1.5	45	C ₂₅	1200	1.5	45
C ₈	800	1.5	90	C ₁₇	1000	1.5	90	C ₂₆	1200	1.5	90
C ₉	800	1.5	140	C ₁₈	1000	1.5	140	C ₂₇	1200	1.5	140

2.3.2 Entropy method for criteria weighting

In MCDM problems, the significance level of each criteria cannot be the same. A weighting value must be specified for each criterion to evaluate this significance level. Several objective weighting methods are proposed by researchers. One of the most prominent of them is the entropy method. This method is based on the concept of Entropy, which is defined as a measure of uncertainty by Shannon.⁵¹ In the information theory, entropy is a criterion for the level of uncertainty given by discrete probability distribution, such that, the ones with significantly high values exhibit higher levels of uncertainty.⁵² If the decision matrix with sufficient information for the alternatives is available, then the entropy method can be used as a tool to determine the significance rankings, i.e., the weighting values of the criteria.^{28,53–55} The method can be summarized as follows:^{56–57}

Let the decision matrix for a multi-criteria decision making problem with *m* alternatives and *n* criteria be Equation (1):

$$D = \begin{matrix} & X_1 & X_2 & \dots & X_j & \dots & X_n \\ \begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_i \\ \vdots \\ A_m \end{matrix} & \left[\begin{matrix} x_{11} & x_{12} & \dots & x_{1j} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2j} & \dots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{i1} & x_{i2} & \dots & x_{ij} & \dots & x_{in} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \dots & x_{mj} & \dots & x_{mn} \end{matrix} \right] \end{matrix} \quad (1)$$

Here, *x_{ij}*: is the success value of *i*-th alternative according to *j*-th criterion. *i* = 1,2,...,*m* and *j* = 1,2,...,*n*.

Here, *A* and *X* stand for the alternative and the criterion, respectively.

Step 1:

With the following Equation (2):

$$r_{ij} = \frac{x_{ij}}{\sum_{p=1}^m x_{pj}} \quad i = 1,2,\dots,m \text{ and } j = 1,2,\dots,n \quad (2)$$

R = [*r_{ij}*]_{*m* × *n*} normalized decision matrix is obtained.

Step 2:

With the following Equation (3):

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^m r_{ij} \ln r_{ij} \quad j = 1, 2, \dots, n \quad (3)$$

entropy value of each criterion is found. Here, e_j is the entropy value of the j the criterion.

Step 3:

The weighting values of the criteria are assigned with Equation (4):

$$W_j = \frac{1 - e_j}{\sum_{p=1}^n (1 - e_p)} \quad j = 1, 2, \dots, n \quad (4)$$

It is apparent that $\sum_{j=1}^n W_j = 1$

3 RESULTS AND DISCUSSION

In this study, TOPSIS, MAUT and CP methods among the MDCM methods are used with the wear results obtained from the conducted micro-abrasion tests for the selection of the most suitable coating material, and afterwards the solutions proposed by each method are compared.

First, the criteria were weighted through the implementation of the Entropy method on the decision matrix

(Table 7) consisting of the test results obtained from the micro-abrasion tests conducted in accordance with the test parameters given in Table 3, and then the analyses were carried out for each of the TOPSIS, MAUT and CP methods, as a means for the selection of the most suitable coating material. The resulting solutions were listed in descending order (from the most to the least suitable) by a comparative evaluation.

The criterion weights obtained with the Entropy method are given in Table 8.

The criteria weights were objectively determined with the Entropy method. The criteria weights calculated using the Entropy method are given in Table 8. According to these results, the criterion weights of the 26th, 22nd, 25th and 19th criteria were found to be higher than the other criteria. This arises from the fact that the 7th alternative Uncoated sample and 1st alternative CrN coating result in relatively higher wear rates, whereas N+CrN, TiAlN and TiN coatings result in lower wear rates. Consequently, the coatings providing lower wear rates under these criteria are favored over the other coatings. Other criterion weights generally had approximate values.

3.1 Analysis using TOPSIS method

The Technique for order preference by similarity to ideal solution (TOPSIS) method developed by C. - L. Hwang and K. Yoon²⁸ is based on the basic concept of

Table 7: The decision matrix for coating-material selection

Tabela 7: Matrica odločitev pri izbiri materiala nanosa

Material	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	
CrN	0.0097	0.0134	0.0135	0.0149	0.0195	0.0221	0.0169	0.0226	0.0267	0.0071	0.0047	0.0044	0.0050	
N+CrN	0.0047	0.0061	0.0066	0.0073	0.0099	0.0106	0.0104	0.0096	0.0094	0.0016	0.0013	0.0055	0.0078	
N+TiAlN	0.0060	0.0071	0.0074	0.0055	0.0067	0.0077	0.0043	0.0067	0.0123	0.0031	0.0079	0.0020	0.0054	
N+TiN	0.0042	0.0060	0.0093	0.0085	0.0129	0.0161	0.0088	0.0185	0.0189	0.0015	0.0037	0.0059	0.0026	
TiAlN	0.0030	0.0050	0.0073	0.0059	0.0119	0.0111	0.0073	0.0130	0.0190	0.0013	0.0024	0.0075	0.0019	
TiN	0.0041	0.0059	0.0083	0.0070	0.0093	0.0130	0.0074	0.0156	0.0108	0.0042	0.0061	0.0065	0.0039	
Uncoated	0.0094	0.0147	0.0147	0.0220	0.0214	0.0228	0.0196	0.0220	0.0267	0.0081	0.0102	0.0122	0.0117	
Material	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26	C27
CrN	0.0055	0.0072	0.0100	0.0064	0.0118	0.0021	0.0024	0.0013	0.0020	0.0021	0.0022	0.0024	0.0021	0.0029
N+CrN	0.0058	0.0093	0.0051	0.0036	0.0094	0.0005	0.0006	0.0009	0.0008	0.0006	0.0006	0.0005	0.0003	0.0004
N+TiAlN	0.0092	0.0026	0.0054	0.0068	0.0050	0.0003	0.0008	0.0005	0.0004	0.0015	0.0007	0.0009	0.0010	0.0005
N+TiN	0.0018	0.0117	0.0065	0.0016	0.0064	0.0009	0.0011	0.0015	0.0011	0.0014	0.0009	0.0012	0.0017	0.0012
TiAlN	0.0056	0.0054	0.0012	0.0028	0.0034	0.0015	0.0006	0.0006	0.0004	0.0004	0.0007	0.0004	0.0004	0.0007
TiN	0.0045	0.0011	0.0072	0.0092	0.0090	0.0004	0.0009	0.0012	0.0005	0.0007	0.0006	0.0006	0.0007	0.0008
Uncoated	0.0139	0.0246	0.0164	0.0166	0.0255	0.0048	0.0049	0.0024	0.0053	0.0030	0.0040	0.0055	0.0067	0.0027

Table 8: The criterion weights obtained using the entropy method

Tabela 8: Kriterijske uteži, dobljene z metodo entropije

Criterion	C1	C2	C3	C4	C5	C6	C7	C8	C9
Weight	0.0158	0.0163	0.0082	0.0245	0.0131	0.0120	0.0203	0.0126	0.0131
Criterion	C10	C11	C12	C13	C14	C15	C16	C17	C18
Weight	0.0403	0.0297	0.0196	0.0279	0.0259	0.0571	0.0321	0.0414	0.0357
Criterion	C19	C20	C21	C22	C23	C24	C25	C26	C27
Weight	0.0758	0.0616	0.0219	0.0866	0.0353	0.0540	0.0790	0.0922	0.0482

the selection of the alternative closest to ideal solution and the farthest to anti-ideal solution. The consecutive stages of this method are as follows:^{28,56}

Step 1: Constructing the normalized decision matrix: with the following Equation (5):

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{p=1}^m (x_{pj})^2}} \quad i = 1, 2, \dots, m \text{ and } j = 1, 2, \dots, n \quad (5)$$

Normalized decision matrix $R = [r_{ij}]$ is obtained.

Step 2: Constructing the weighted normalized decision matrix, with the following Equation (6):

$$v_{ij} = w_j r_{ij} \quad i = 1, 2, \dots, m \text{ and } j = 1, 2, \dots, n \quad (6)$$

Normalized decision matrix $V = [v_{ij}]_{m \times n}$ is obtained.

Here, w_j : j -th criterion's weight value obtained with the entropy method.

Step 3: Determination of ideal and negative-ideal solutions:

If the two artificial solutions A^* (ideal solution) and A^- (negative-ideal solution) are defined as follows:

$$A^* = \left\{ (\max_i v_{ij} | j \in J), (\min_i v_{ij} | j \in J') | i = 1, 2, \dots, m \right\} \quad (7)$$

$$= \{v_1^*, v_2^*, \dots, v_j^*, \dots, v_n^*\}$$

$$A^- = \left\{ (\min_i v_{ij} | j \in J), (\max_i v_{ij} | j \in J') | i = 1, 2, \dots, m \right\} \quad (8)$$

$$= \{v_1^-, v_2^-, \dots, v_j^-, \dots, v_n^-\}$$

here,

$$J = \{j = 1, 2, \dots, n | \text{in case of benefit criterion}\}$$

$$J' = \{j = 1, 2, \dots, n | \text{in case of cost criterion}\}$$

Step 4: Calculation of the separation measure:

Each alternative's measure of separation from the ideal solution S_i^+ and from the negative-ideal solution S_i^- , is given as follows:

$$S_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^*)^2}, \quad i = 1, 2, \dots, m \quad (9)$$

$$S_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2}, \quad i = 1, 2, \dots, m \quad (10)$$

Step 5: Calculation of the relative proximity to the ideal solution:

The relative proximity to the i -th alternative to the ideal solution (A^*) is defined as follows:

$$C_i^+ = S_i^- / (S_i^+ + S_i^-), \quad 0 < C_i^+ < 1, \quad i = 1, 2, \dots, m \quad (11)$$

Step 6: Performing the decision ranking: The decision ranking of the alternatives is performed in accordance with the descending order of C_i^+ values.

The weighted and normalized decision matrix, related to the analysis conducted in accordance with the steps defined in the TOPSIS method, is given in **Table 9**. Ideal and anti-ideal solutions obtained using Equations (7) and (8), are given in **Table 10**. As indicated in the table, the highest C_i^+ valued alternative stands for the best selection in the TOPSIS method.

Positive and negative separation measures given in **Table 11** and relative proximities to the ideal solution are calculated respectively with Equations (9), (10) and (11). Also, the ranking of the coating materials based on the relative proximities to ideal solution are given in **Table 11**. According to this ranking, TiAlN is qualified as the best coating material owing to its excellent performance, which is followed by N+CrN, TiN and N+TiAlN with similar performance values. N+TiN and CrN resulted in low performance values, whereas the uncoated material resulted in the worst performance value.

Table 9: Weighted normalized decision matrix

Tabela 9: Pretehtana normalizirana matrica odločitev

Material	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	
CrN	0.0091	0.0091	0.0042	0.0118	0.0069	0.0063	0.0109	0.0066	0.0070	0.0235	0.0089	0.0047	0.0083	
N+CrN	0.0044	0.0041	0.0020	0.0058	0.0035	0.0030	0.0067	0.0028	0.0024	0.0053	0.0024	0.0059	0.0130	
N+TiAlN	0.0056	0.0048	0.0023	0.0044	0.0024	0.0022	0.0028	0.0020	0.0032	0.0102	0.0150	0.0021	0.0091	
N+TiN	0.0039	0.0041	0.0029	0.0068	0.0045	0.0046	0.0057	0.0054	0.0049	0.0048	0.0069	0.0063	0.0044	
TiAlN	0.0028	0.0034	0.0023	0.0047	0.0042	0.0032	0.0047	0.0038	0.0050	0.0042	0.0045	0.0080	0.0032	
TiN	0.0038	0.0040	0.0026	0.0056	0.0033	0.0037	0.0048	0.0045	0.0028	0.0137	0.0116	0.0070	0.0065	
Uncoated	0.0088	0.0100	0.0046	0.0175	0.0075	0.0066	0.0127	0.0064	0.0070	0.0267	0.0192	0.0131	0.0196	
Material	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26	C27
CrN	0.0072	0.0135	0.0141	0.0121	0.0132	0.0289	0.0257	0.0080	0.0292	0.0171	0.0244	0.0304	0.0259	0.0325
N+CrN	0.0076	0.0175	0.0072	0.0069	0.0105	0.0065	0.0062	0.0053	0.0115	0.0046	0.0069	0.0058	0.0037	0.0044
N+TiAlN	0.0119	0.0048	0.0075	0.0130	0.0055	0.0038	0.0082	0.0032	0.0055	0.0127	0.0073	0.0111	0.0122	0.0051
N+TiN	0.0023	0.0220	0.0092	0.0030	0.0070	0.0128	0.0112	0.0093	0.0159	0.0114	0.0104	0.0155	0.0209	0.0133
TiAlN	0.0073	0.0101	0.0017	0.0053	0.0037	0.0206	0.0062	0.0036	0.0055	0.0030	0.0082	0.0051	0.0044	0.0073
TiN	0.0058	0.0020	0.0102	0.0176	0.0100	0.0048	0.0096	0.0073	0.0069	0.0059	0.0066	0.0070	0.0088	0.0089
Uncoated	0.0181	0.0464	0.0231	0.0316	0.0283	0.0651	0.0526	0.0149	0.0784	0.0243	0.0447	0.0696	0.0845	0.0302

Table 10: Ideal and anti-ideal solutions

Tabela 10: Idealne in neidealne rešitve

Criterion	C1	C2	C3	C4	C5	C6	C7	C8	C9
A*	0.0028	0.0034	0.0020	0.0044	0.0024	0.0022	0.0028	0.0020	0.0024
A-	0.0091	0.0100	0.0046	0.0175	0.0075	0.0066	0.0127	0.0066	0.0070
Criterion	C10	C11	C12	C13	C14	C15	C16	C17	C18
A*	0.0042	0.0024	0.0021	0.0032	0.0023	0.0020	0.0017	0.0030	0.0037
A-	0.0267	0.0192	0.0131	0.0196	0.0181	0.0464	0.0231	0.0316	0.0283
Criterion	C19	C20	C21	C22	C23	C24	C25	C26	C27
A*	0.0038	0.0062	0.0032	0.0055	0.0030	0.0066	0.0051	0.0037	0.0044
A-	0.0651	0.0526	0.0149	0.0784	0.0243	0.0447	0.0696	0.0845	0.0325

Table 11: Positive and negative separation measures, relative proximities to the ideal solution and the ranking

Tabela 11: Pozitivni in negativni ukrepi ločevanja, relativni približki idealni rešitvi in razvrstitve

Material	S+	S-	C+	Sýra
CrN	0.0724	0.1104	0.6039	6
N+CrN	0.0234	0.1632	0.8747	2
N+TiAlN	0.0262	0.1610	0.8602	4
N+TiN	0.0371	0.1433	0.7946	5
TiAlN	0.0212	0.1648	0.8861	1
TiN	0.0255	0.1620	0.8640	3
Uncoated	0.1742	0.0023	0.0132	7

3.2 Analysis using MAUT method

According to the basic principle of MAUT (Multiple Attribute Utility Theory) method, there is an U utility function with a real value, defined over the set of suitable alternatives, and the decision maker maximizes this.⁵⁸ The procedure followed in the MAUT method is defined in 4 steps:^{59–60}

Step 1: Utility values are determined according to the benefit criteria and the normalized values r_{ij} are calculated using these values:

$$r_{ij} = \frac{x_{ij} - l_j^-}{u_j^+ - l_j^-}, u_j^+ = \max_i x_{ij}, l_j^- = \min_i x_{ij} \quad (12)$$

Similarly, the utility values are also determined based on the cost criterion, and normalized values r_{ij} are calculated accordingly:

$$r_{ij} = \frac{u_i^+ - x_{ij}}{u_i^+ - l_i^-}, u_i^+ = \max_j x_{ij}, l_i^- = \min_j x_{ij} \quad (13)$$

Step 2: Weighted sum of r_{ij} values gives the total utility value.

$$U_i = \sum_{j=1}^n w_j r_{ij} \quad (14)$$

Step 3: Decision ranking is performed. The alternative with the highest total utility value is deemed the best alternative.

The single-attribute utility function values of the alternatives calculated with MAUT method based on the criteria, are given in **Table 12**.

MAUT multi-attribute utility function values and their ranking are given in **Table 13**. As shown in Table

Table 12: MAUT single-attribute utility function values

Tabela 12: Posamezni MAUT-atributi vrednosti funkcije koristnosti

Material	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	
CrN	0.0000	0.1299	0.1556	0.4352	0.1283	0.0498	0.1777	0.0000	0.0000	0.1428	0.6139	0.7683	0.6856	
N+CrN	0.7483	0.8835	1.0000	0.8920	0.7841	0.8094	0.6014	0.8183	1.0000	0.9493	1.0000	0.6587	0.3997	
N+TiAlN	0.5519	0.7813	0.8990	1.0000	1.0000	1.0000	1.0000	1.0000	0.8310	0.7342	0.2495	1.0000	0.6384	
N+TiN	0.8212	0.8924	0.6653	0.8215	0.5769	0.4445	0.7070	0.2588	0.4521	0.9742	0.7299	0.6205	0.9282	
TiAlN	1.0000	1.0000	0.9083	0.9812	0.6450	0.7784	0.8047	0.6033	0.4462	1.0000	0.8771	0.4622	1.0000	
TiN	0.8332	0.9034	0.7956	0.9099	0.8235	0.6514	0.7982	0.4395	0.9160	0.5800	0.4557	0.5562	0.7969	
Uncoated	0.0450	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0399	0.0000	0.0000	0.0000	0.0000	0.0000	
Material	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26	C27
CrN	0.6906	0.7401	0.4203	0.6811	0.6160	0.5904	0.5791	0.5917	0.6755	0.3393	0.5349	0.6074	0.7250	0.0000
N+CrN	0.6669	0.6501	0.7451	0.8653	0.7248	0.9560	0.9991	0.8200	0.9174	0.9229	0.9944	0.9889	1.0000	1.0000
N+TiAlN	0.3921	0.9361	0.7284	0.6518	0.9275	1.0000	0.9580	1.0000	1.0000	0.5444	0.9827	0.9071	0.8948	0.9741
N+TiN	1.0000	0.5491	0.6526	1.0000	0.8645	0.8520	0.8925	0.4780	0.8575	0.6050	0.9001	0.8378	0.7873	0.6851
TiAlN	0.6856	0.8163	1.0000	0.9198	1.0000	0.7259	1.0000	0.9622	1.0000	1.0000	0.9589	1.0000	0.9915	0.8953
TiN	0.7755	1.0000	0.6055	0.4903	0.7436	0.9834	0.9266	0.6537	0.9804	0.8625	1.0000	0.9698	0.9372	0.8410
Uncoated	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0822

13, TiAlN takes the first place with its superior performance, followed by N+CrN, N+TiAlN and TiN with similar performance values. N+TiN, CrN and especially uncoated material exhibited significantly low performances, as the highest total utility valued alternative stands for the best selection.

Table 13: MAUT Multi-utility function and the ranking
Tabela 13: MAUT Večvrednostna funkcija in razvrstitev

Material	Multi utility values	Ranking
CrN	0.509431	6
N+CrN	0.879946	2
N+TiAlN	0.860277	3
N+TiN	0.784909	5
TiAlN	0.909513	1
TiN	0.841247	4
Uncoated	0.005178	7

3.3. Analysis using CP method

CP (Compromise Programming) is a MCDM method developed in the 1970s by M. Zelen⁶¹ and P. – L. Yu.⁶² This method is based on minimization of the distance to the ideal point f^* . The L_p metric is used for the calculation of distance. The method can be summarized as follows:^{63–66}

Step 1: Ideal point f^* and anti-ideal point f_* are established.

$$f^* \equiv f_1^*, f_2^*, \dots, f_n^*, f_* \equiv f_{1*}, f_{2*}, \dots, f_{n*} \quad (15)$$

here,

$$f_j^* = \begin{cases} \max_{i=1,2,\dots,m} \{x_{ij}\} & j. \text{ criterion utility} \\ \min_{i=1,2,\dots,m} \{x_{ij}\} & j. \text{ criterion cost} \end{cases} \quad (16)$$

$$f_{j*} = \begin{cases} \min_{i=1,2,\dots,m} \{x_{ij}\} & j. \text{ criterion utility} \\ \max_{i=1,2,\dots,m} \{x_{ij}\} & j. \text{ criterion cost} \end{cases} \quad (17)$$

here, x_{ij} : is the success value of the i -th alternative according to the j -th criterion. $i = 1, 2, \dots, m, j = 1, 2, \dots, n$.

Step 2: The distance to the ideal point is minimized:

$$\min L_p = \left[\sum_{j=1}^n W_j \left(\frac{f_j^* - f_j(x_i)}{f_j^* - f_{j*}} \right)^p \right]^{1/p}, \quad i = 1, 2, \dots, m \quad (18)$$

Step 3: The alternative giving the minimal value is the best alternative.

L_1, L_2 and L_∞ are, respectively, named as the Manhattan, Euclidean and Tchebycheff metrics.

The optimal values obtained using the CP method and the ranking are shown in **Table 14**. Given that in the CP method the alternative giving the lowest optimal value is the best alternative; TiAlN may be considered to have shown the best performance by far, as the highest total utility valued alternative stands for the best selection. N+CrN, N+TiAlN and TiN materials underperformed compared to the performance values of TiAlN.

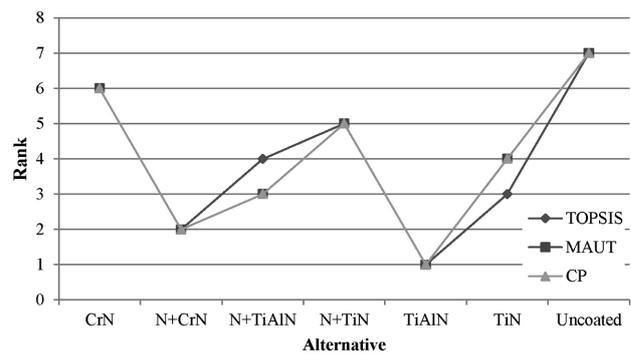


Figure 3: Ranking of the alternatives obtained with MCDM methods
Slika 3: Razvrstitev alternativnih variant, dobljenih z MCDM metodami

The performance values of N+TiN, CrN and the uncoated materials lined up at the bottom of the performance list.

Table 14: CP optimal values and the ranking
Tabela 14: CP optimalne vrednosti in razvrstitev

Material	Optimal value	Rank
CrN	0.269379	6
N+CrN	0.070013	2
N+TiAlN	0.080999	3
N+TiN	0.120416	5
TiAlN	0.055632	1
TiN	0.089914	4
Uncoated	0.543521	7

The rankings obtained using the TOPSIS, MAUT and CP methods are shown in **Figure 3**. As seen in the figure, the MAUT and CP methods produced the identical ranking of the alternatives, whereas there is a slight deviation in the ranking obtained with the TOPSIS method. However, all the methods indicate that TiAlN is the best material, followed by N+CrN. CrN and the uncoated materials displayed the best performances, according to all the MCDM methods implemented in the study.

4 CONCLUSIONS

In this study, abrasive wear tests were conducted using the micro-abrasion wear technique on TiN, CrN and AlTiN coatings, which were deposited on nitrated and non-nitrated substrates with the PVD technique, then the measured wear values were used so as to determine the best coating selection through analyses with each of the TOPSIS, MAUT and CP methods among the MCDM techniques. The most suitable coating types, according to each method, were determined and comparatively evaluated. The obtained results are summarized as follows:

- According to the TOPSIS method TiAlN was determined to be the coating with the best performance; which was followed by N+CrN, TiN and N+TiAlN, respectively. The N+TiN and CrN coatings under-

performed compared to other coatings; however, the uncoated material displayed the worst performance, with a dramatic decline compared to all the coated materials.

- According to the MAUT method, TiAlN exhibited the best performance. Other coatings were ranked as N+CrN, N+TiAlN and TiN, respectively. N+TiN, CrN and especially the uncoated material displayed remarkable underperformances.
- The CP and MAUT methods produced the same ranking of alternatives. In the TOPSIS method only N+TiAlN and TiN shifted places in the ranking differently from the CP and MAUT methods. However, all the methods indicate that TiAlN is the best material, which is followed by N+CrN. Again, the CrN and uncoated materials became the alternatives with worse performances according to all the MCDM methods.
- The highest C_1^* valued alternative is deemed the best selection in the TOPSIS method. While the highest total utility valued alternative is the best selection for MAUT, in the CP method the shortest distance is favored.
- Increasing the number of MCDM methods could be useful for a comparative analysis of the obtained results in further studies.

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