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A HYBRID MEREC-TOPSIS APPROACH FOR THE IMPROVEMENT OF PHYSICAL VAPOUR DEPOSITED TITANIUM CARBO-NITRIDE COATING

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Abstract

Titanium carbo-nitride (TiCN) comes under the metal nitride group which can provide a combined property of titanium carbide (TiC) and titanium nitride (TiN) coating. TiCN Coating possess an excellent mechanical and tribological, properties which leads its application in many industries particularly in the Automotive and aerospace industries. TiCN films can be very hard and strong based on the composition and synthesis process. Physical Vapor Deposition (PVD) technique is widely used for the preparation of thin film coating because of its ability to precisely control the composition and thickness of the coatings. The properties of the developed coating significantly affect by the PVD process parameters and their levels. Multi-Criteria Decision Making (MCDM) methods are widely used in many sectors for the selection of process parameters based upon some specific criteria. In the present work TiCN coatings were synthesized by using one of the most widely used PVD method called magnetron sputtering. L16 orthogonal array was used as a design of experiment for the experimental work by varying the sputtering process parameters like bias voltage, N_2 flow rate and substrate to target distance. After the synthesis, the developed films were tested using atomic force microscopy (AFM), Scanning electron microscopy (SEM), and Nanoindentation. From the characterization three response parameters such as hardness (H), Modulus of elasticity (E) and surface roughness (Ra) of the coating has been considered. A hybrid method based on improved removal effects of criteria- technique for order performance by similarity to ideal solution (MEREC-TOPSIS) approach has been considered for the for the process parameters selection. The results have also been compared with other weight calculation techniques. In all the cases it is observed that experiment no 16 and 15 have got the 1st and second rank respectively. However, experiment no 1 is the last rank in all the cases. From the correlation analysis it is found a strong positive correlation between MEREC-TOPSIS and other methods. The method provides a significant advancement in the selection of optimal parameters, ensuring enhanced coating properties crucial for industrial applications

Keywords:

TiCN coating, MCDM, MEREC-TOPSIS, PVD, Sputtering.

1 INTRODUCTION

Titanium carbonitride (TiCN) thin films have high hardness with excellent thermal, structural and chemical stability. These coatings are widely used in numerous industries as a protective layer to enhance the surface wear resistance such as engine parts and cutting tools [Shakib 2023, Ortiz 2023, Alipovna 2023]. For the protective coating many films such as Titanium nitride (TiN), Titanium silicon carbonitride (TiSiCN), Titanium carbonitride (TiCN), diamond like carbon (DLC) etc have gained the attention in the past years [Das 2020]. TiCN is popular among all because it combines the advantages of both TiN and TiC coating. Many researchers have already proof that TiCN coating is considered as a vital protective coating materials for the high temperatures and corrosive environments [Qin 2020]. The TiCN composition available in a wide range in the form $TiC_{1-x}N_x$, in which the range of x lies between 0-1. Here the coating hardness mainly depends on the crystal structure as well as the number of vacancies on the carbon and Nitrogen sites [Sundgren 1985]. Various methods like physical vapor deposition (PVD), ion beam assisted deposition, chemical vapor deposition (CVD) are widely used for the synthesis of TiCN coatings.

In the recent years, methods based on Physical Vapor Deposition (PVD) processes have been widely used for the synthesis of thin film coating because of its ability to precisely control the composition and thickness of the coatings. The properties of the developed coating significantly affect by the PVD process parameters and their levels. In PVD the parameters like bias voltage, substrate temperature, gas flow rate, sputtering power, substrate to target distance have a significant affect the properties of the coatings. Selection of these parameters and their value is a challenging task for the thin film coating researchers. Many researchers use heat and trial method to select the parameters and their values [Atta 2023].

Multi-criteria decision-making (MCDM) is one of the robust methods for the selection of parameters in various areas.MCDM has many methods which can be applied in various fields from management to engineering design. Researchers from the management background often use various MCDM techniques to find the best alternative among many. In MCDM techniques various weight calculation methods are used to provide the weightage to various criteria. There are different weight calculation techniques like entropy method, standard deviation method, mean method etc. which can be integrated with the MCDM techniques to give the ranking of alternatives. However, in the field of material science and nanotechnology very few have used such techniques in their research work. Ghadai et al. used different MCDM techniques, like grey relational analysis (GRA), Mult objective optimisation on the basis of ratio analysis (MOORA), and technique for order preference by similarity to ideal solution (TOPSIS) to optimize the milling process parameters for the machining of Al 1070 [Ghadai 2023]. Yeng et al. used grey-fuzzy and Taguchi approach to optimize the CVD process parameters for the synthesis of Zr-DLC coatings [Zou 2011]. Singh and Jatti used Taguchi approach for the optimal CVD process parameter for the synthesis of protective diamond like carbon (DLC) coatings [Singh 2015].

From the above literature it is observed that few MCDM techniques are used for the improvement of thin film coating synthesize by various CVD method [Ghadai 2023, Zou 2011, Singh 2015, Kalita 2022a]. However rare literatures are available for the optimization of PVD parameters for the synthesis of TiCN coatings. Therefore, current work is basically deal with the use of hybrid MEREC-TOPSIS Approach for the improvement of Physical Vapor Deposited TiCN coatings.

2 EXPERIMENTAL DETAILS

TThe experimental data in the present study has been considered from the published work by Das et al. [Das 2023]. L16 orthogonal array was used as a design of experiment for the experimental work by varying the sputtering process parameters like bias voltage, N_2 flow rate and substrate to target distance (STD). After the synthesis, the developed coatings.

3 METHODOLOGY

3.1 MEREC

MEREC is a recent developed method by Keshavarz-Ghorabae et al. [Keshavarz-Ghorabaee 2021] to compute the objective weights for the criteria in MCDM scenarios. The MEREC can be executed by following the steps mentioned below—

1. Specify the MCDM problem in form of a decision matrix (X) made up of elements x_{ij}

2. Derive the normalized decision matrix (N) from (X) using n_{ij}^x

$$n_{ij}^x = \begin{cases} \frac{\min_k x_{kj}}{x_{ij}} \text{ if } j \in \text{Beneficial} \\ \frac{x_{ij}}{\max_k x_{kj}} \text{ if } j \in \text{Non} - \text{Beneficial} \end{cases} \quad (1)$$

3. Compute the S_i scores for ith alternative as

$$S_i = \ln\left(1 + \left(\frac{1}{m}\sum_j \left|\ln\left(n_{ij}^x\right)\right|\right)\right) \quad (2)$$

4. Compute S'_{ij} for ith alternative as

$$S'_{ij} = \ln\left(1 + \left(\frac{1}{m}\sum_{k,k\neq j} \left|\ln(n_{ik}^x)\right|\right)\right) \quad (3)$$

5. Compute E_j for jth criterion as

$$E_j = \sum_i | S'_{ij} - S_i | \quad (4)$$

6. Ascertain w_j for jth criterion as

$$w_j = \frac{E_j}{\sum_k E_k} \quad (5)$$

3.2 TOPSIS

TOPSIS [Hwang 2012] is a popular multi-criteria decision-making technique. It uses the concept of Euclidian distance from best and worst solution to rank each solution.A solution with larger distance from the negative ideal solution and small distance from the positive ideal solution is preferred [Kalita 2022b, Shivakoti 2017].

The problem based on $m$number of alternate and $n$number of criteria, let $D = x_{ij}$ is a decision matrix, where $x_{ij} \in \mathbb{R}$

$$D = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (6)$$

The weight vector in the present study may be stated as,

$$w_j = [w_1 \quad \cdots \quad w_n] \text{ where } \sum_{j=1}^{n}(w_1 \quad \cdots \quad w_n) = 1. \quad (7)$$

Once the decision matrix is framed and the weight criterion for each response is determined using equation (6) & (7), normalization of the matrix will be calculated using equation (8) and the weighted matrix of normalized value is estimated using equation (9)

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad (8)$$

$$N_{ij} = w_j * n_{ij} \quad (9)$$

where $i \in [1, m]$ and $j \in [1, n]$.

The best (ideal positive) and worst (ideal negative) values are calculated using equation (10) and equation (11) respectively.

$$A_j^+ = \begin{cases} \max. N_{ij} \mid j \in B \\ \min. N_{ij} \mid j \in C \end{cases} \quad (10)$$

$$A_j^+ = \begin{cases} \min. N_{ij} \mid j \in B \\ \max. N_{ij} \mid j \in C \end{cases} \quad (11)$$

The each process characteristics difference from best and worst value is then calculated with the help of equation (12) and (13) respectively.

$$S_i^+ = \sqrt{\sum_{j=1}^{n} (N_{ij} - A_j^+)^2} \quad \text{for} \quad i \in [1, m] \quad \text{and} \quad j \in [1, n] \tag{12}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} (N_{ij} - A_j^-)^2} \text{ for } i \in [1, m] \text{ and } j \in [1, n] \tag{13}$$

The corresponding closeness coefficient (CC_i) of the i[th] alternative is calculated using eqn. (14)

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-} \text{ where } 0 \le CC_i \le 1, i \in [1, m] \tag{14}$$

The alternatives are ranked on the basis of reducing value of CC_i.

4 RESULTS AND DISCUSSION

The experiments indicated in Table 1 were carried out utilizing the L16 orthogonal array to modify sputtering process parameters such as bias voltage, nitrogen flow rate and substrate to target distance, have produced significant insights into the properties of Titanium Carbo-Nitride (TiCN) coatings. The experimental results are summarized in Table 1, which presents the variation in hardness, Young's modulus and surface roughness in response to the different parameter settings.

The hybrid MEREC-TOPSIS approach was employed to select optimal process parameters. However, to build more confidence into the computed results and to assess the effect of weights on optimal parametric combination, five additional weight allocation methods were considered. Table 2 shows the weights as computed by six different methods, i.e., Equal, Entropy, Standard deviation, Gini, CRITIC and MEREC. Figure 1 shows the variation in weights of each criterion due to different methods. For example, for C1 criterion i.e., Hardness the weights are seen to vary between 0.1 to 0.333 whereas for C2 criterion i.e., Young's modulus the weights vary between 0.1 to 0.8. On the other hand, the weights for C3 criterion i.e., Surface roughness varies between 0.1 to 0.8. The comparative results demonstrated strong positive correlations of MEREC with other weight calculation methods, indicating robustness and reliability. Figure 2 illustrates these correlations, affirming the consistency of the proposed method with established techniques.

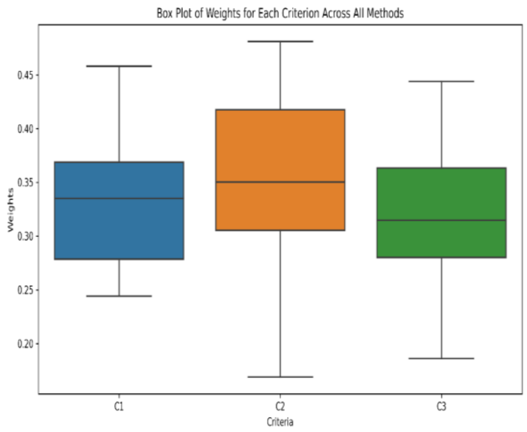

Fig. 1: Box plot of criteria wise weights as calculated by different methods.

Figure 3 and Figure 4 respectively display the variations of S_i^+ and S_i^-scores and the closeness coefficients (CC_i) across different experiments, providing a visual assessment of the parameter impact on the coating quality. Notably, experiment 16, featuring the highest hardness and Young's modulus, ranked top in the current analysis, suggesting that higher substrate to target distance and maximum bias voltage favourably influence coating properties.

The effectiveness of the MEREC-TOPSIS method in this context lies in its nuanced consideration of multiple criteria, which is critical for complex engineering applications like thin film coating. The method's ability to derive objective weights for each criterion based on decision matrix transformations and subsequent ranking processes ensures a comprehensive evaluation of the alternatives.

Comparative analysis with other MCDM methods, such as Entropy, Standard Deviation and CRITIC, confirms that the proposed hybrid approach not only aligns with but sometimes surpasses these methods in capturing the nuances of PVD process optimization for TiCN coatings. The robustness of MEREC-TOPSIS is particularly evident in its high correlation with traditionally used methods, as shown in the derived results [Das 2023].

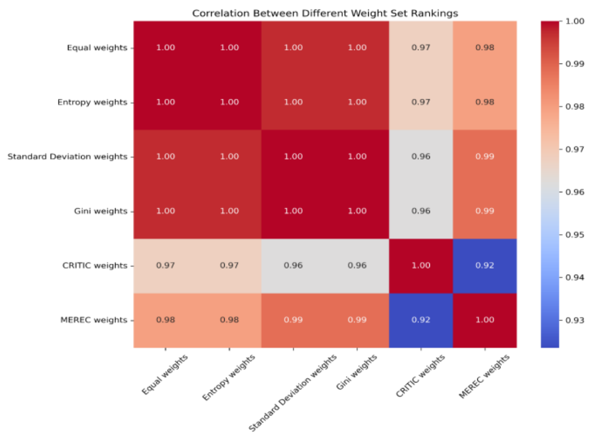

Fig. 2: Box plot of criteria wise weights as calculated by different methods

This research not only contributes to the body of knowledge on PVD coatings but also enhances practical applications in industries where TiCN coatings are crucial for improving the durability and performance of machine parts. The implications extend to better product designs and longer lifecycle for components in automotive and aerospace sectors, which are increasingly reliant on advanced material coatings for operational efficiency and longevity.

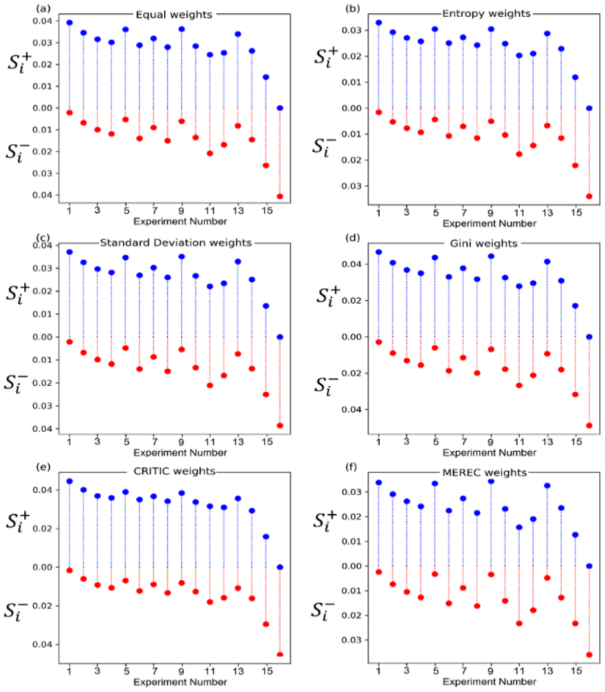

Fig. 3: Variation of S_i^+ and S_i^- with various weights.

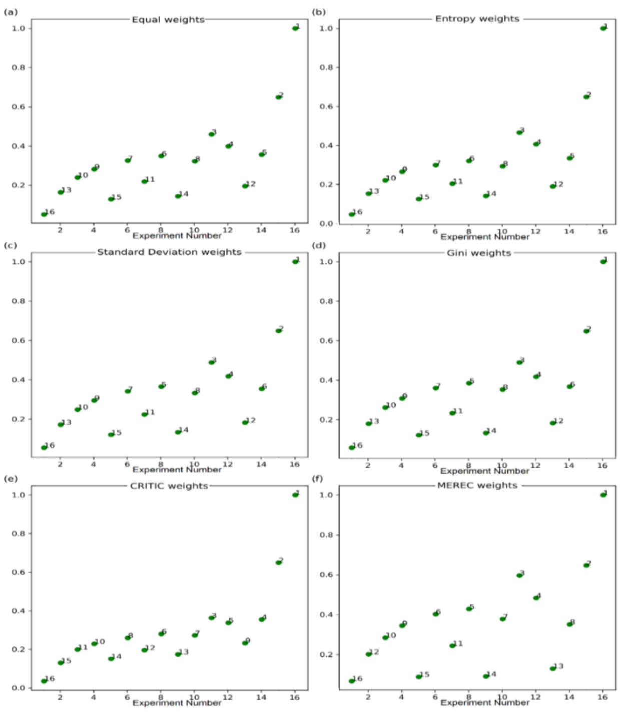

Fig. 4: Variation of CC_i with various weights (Numbers inside the plot indicate rank of the respective alternative i.e., experiment number).

5 CONCLUSION

The current study confirms the utility of the hybrid MEREC-TOPSIS approach for optimizing PVD process parameters in the production of TiCN coatings. In all the cases it is observed that experiment no 16 and 15 have got the 1st and second rank respectively. However, experiment no 1 is the last rank in all the cases. The method provides a significant advance in the selection of optimal parameters, ensuring enhanced coating properties crucial for industrial applications. Future work will focus on refining the decision matrix and exploring the integration of additional criteria to further validate and extend the applicability of this MCDM approach in materials engineering.

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Table 1 : Input and Response parameters as per L16 design of experiment [12]

	Input Parameter			Response Parameters		
Exp.	**STD (mm)**	**Nitrogen Flow Rate (sccm)**	**Bias Voltage (V)**	**H(GPa)**	**E (GPa)**	**Surface roughness R_a(micron)**
1	20	10	−120	16.23	178.27	7.78
2	20	15	−100	17.11	180.18	7.56
3	20	20	−80	17.67	180.43	7.39
4	20	25	−60	18.07	182.52	7.37
5	30	10	−100	16.06	177.56	7.34
6	30	15	−120	18.56	181.67	7.34
7	30	20	−60	17.34	180.22	7.34
8	30	25	−80	18.74	182.11	7.29
9	40	10	−80	15.78	177.84	7.26
10	40	15	−60	18.34	180.45	7.23
11	40	20	−120	19.79	192.76	7.22
12	40	25	−100	18.78	189.43	7.11
13	50	10	−60	16.11	177.52	7.09
14	50	15	−80	17.89	180.81	6.87
15	50	20	−100	19.37	191.22	6.12
16	50	25	−120	21.34	198.67	5.23

Table 2: Weights as computed by various methods

Weights	**Criteria**		
	C1	**C2**	**C3**
Equal	0.333	0.333	0.333
Entropy	0.25	0.25	0.5
Standard deviation	0.25	0.4	0.35
Gini	0.1	0.1	0.8
CRITIC	0.1	0.8	0.1
MEREC	0.1	0.6	0.3