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OPTIMIZATION OF MECHANICAL AND BIOLOGICAL PROPERTIES OF STEEL-BASED PLD USING AHP-FUZZY APPROACH

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Abstract
The aim of present study is to evaluate the optimum mechanical and biological properties of Steel-based PLD (pulsed laser deposition) using Fuzzy AHP-TOPSIS- based Taguchi Approach. In order to evaluate the optimal option according to L8 Taguchi orthogonal array, the PLD parameters were designed by considering three levels of process parameters (No. of pulse, voltage and distance) to evaluate the optimum characteristics of carbon steel in terms of mechanical properties and biological properties (microhardness and antibacterial tests). Finally, the fuzzy AHP-TOPSIS results manifested that the optimum results are voltage (900 V), No. of Pulse (900) and distance (5 cm), as well as the target parameters are microhardness (545.4 HV) and excellent biological results.
Keywords: Optimization, Taguchi array, Steel-based PLD, AHP-TOPSIS method
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Introduction

In the last decade, nanotechnology attracted many researches in various fields. In this line of nanomaterial processing and manufacturing, traditional deposition was used widely, like Pulse Laser Deposition (PLD), Sputtering, Chemical Vapor Deposition (CVD), Thermal Evaporation Technique (PVD) and sol-gel. Pulse Laser Deposition is considered one of the important techniques due to the simple, cost effect, and efficient results. PLD possess a high quality, better mechanical features as a thin film for nanomaterial processing. It is well known that the thin film can operate in a high pressure environment. In another words, it shows a high flexibility to grow various kinds of the multi-component of compositions than other films with presenting a high quality. In general, the PLD mechanism operation depends on many factors such as the ablation rate that possessed by target surface than promoting the target's constituents for evaporating correspondingly and adhering to the film. Moreover, the simplicity and high flexibility of PLD made it to be considered as one of the most popular mechanisms. On the contrary with other deposition methods, the PLD deposition system can be settled without a complex instrumentation system, fabrication and other system required for deposition. Usually, consistence along with errors can be occurring during the deposition mechanism process. One of the most attractive features of PLD is the reliability and reproducibility than the other traditional methods of fabrication high-temperature superconductivity (HTS) films which requires removing the mentioned inconsistencies, which are solved by the mechanism presented in this work [1]. PLD mechanism requires high-energy pulsed laser to be focused on the desired target that contains the stoichiometry which results vapor that collected on the next to substance. In the PLD process, gases, such as acetylene or methane are required to be used as reactive gases when the target compositions are evaporated to the thin film. Titanium dioxide

(TiO_2) in nanostructured form was used widely in various applications, such as electro-chromic displays, humidity sensors, anodes in production of ion batteries, gas sensors, in the water and air treatment as well as putrefaction, UV filtering in packing and optic material, transparent conductors, self-cleaning coating, antireflection coating, and corrosion protection as barrier layer [2-11]. It is clear that Titanium dioxide (TiO_2) in nanostructured form has a great benefit in various applications. Consequently, a wide number of researchers focused on the methods to produce Titanium dioxide (TiO_2) in nanostructured form.

The present work intended to optimize the mechanical and biological properties of carbon steel using AHP-Fuzzy TOPSIS based on Taguchi-approach applied to the data of PLD. The objectives of microhardness and biological results are maximized.

AHP-Fuzzy TOPSIS Based Taguchi-Approach

In 1980m Saaty developed a new method of electing the optimum decision according to the rank whenever it has various criteria. This method is called Analytical Hierarchy Process (AHP). And, the main concept of such method depends on the expert view to elect a priority scale [12]. In addition, Multiple Criteria Decision Analysis (MCDM) was used frequently in order to analyze quantitative and qualitative criteria [12]. In fact, AHP relies on the view of the expert, in another word; the analysis quality depends on the expert decision. The mentioned method is more accurate to analyze human judgment, in order to obtain a result that does not answer the problem [13]. Fuzzy AHP was developed in the way to minimize the risk of errors that can happen in interpretation [14]. Actually, Fuzzy theory focused on the obscurity information which can present when it comes to choose suppliers that have a non-precise criterion. In fact, Fuzzy AHP is constructed by Fuzzy Logic that has a member with different values of membership which has values between 0 and 1. Extending the characteristic ranges is the main idea in Fuzzy set which is including real intervals 0-1. This membership is indicating that the item has a value between 0-1, it is not only 0 or 1, and all these values represent the item value in the universe. In the opposite of that, a crisp set has only two values 0 or 1. From above, it is concluded that the fuzzy AHP (FAHP) analysis considered as a systematic method that selects alternative items in the opinion of the application of fuzzy concepts and the analysis that depend on a hierarchical structure [15]. Hence, the fuzzy AHP technique was developed from classical AHP and can be called as an advanced analytical method, first proposed by P. J. M. Van Laarhoven and Pedrycz in 1983 [16], to deal with fuzziness as well as uncertainty in the qualitative and quantitative criteria of the difficulties of MCDM [16]. In this method, triangular fuzzy numbers (Figure 1), first explained and described as membership functions by L. A. Zadeh (1971) [17], father of fuzzy set theory, are used as a preference scale (Table 1) in spite of Saaty's scale for wiping out the fuzziness and vagueness to make a decision with precise judgments.

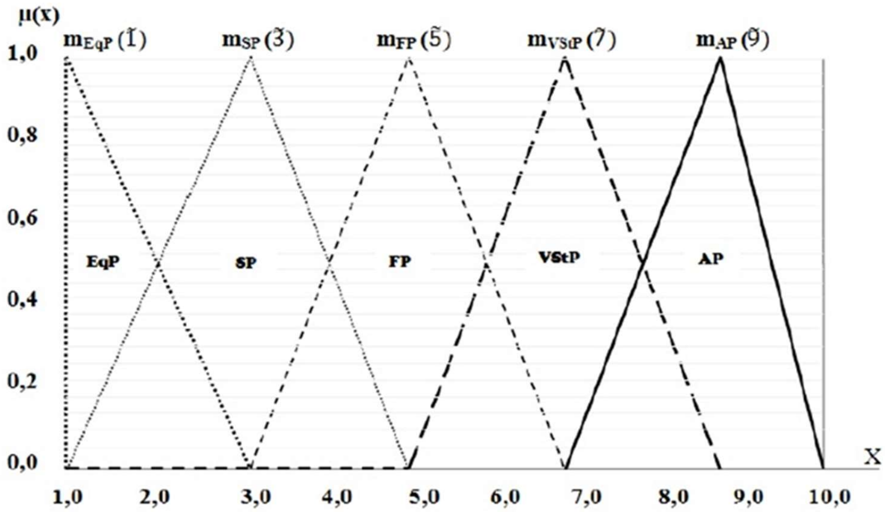

Figure 1. Intensity of importance

Comparative linguistic scale of the weight with the member functions of triangular fuzzy numbers

Table (1): Fuzzy triangular number

Intensity of importance	Fuzzy number	Linguistic terms	Fuzzy triangular number
1	$\tilde{1}$	Equally preferable (EqP)	(1,1,2)
3	$\tilde{3}$	Slightly preferable (SP)	(2,3,4)
5	$\tilde{5}$	Fairly preferable (FP)	(4,5,6)
7	$\tilde{7}$	Very Strongly preferable (VStP)	(6,7,8)
9	$\tilde{9}$	Absolutely preferable (AP)	(8,9,10)

Vague data can be represented in Fuzzy theory beside it can do mathematical along with programming in Fuzzy domain. A grade objects with a membership values multiplicity being described to as fuzzy set. And, a membership function that awards each object a membership grade ranging from zero to one defines such a set. If a sign denotes a fuzzy set, a tilde "~" will appear above the symbol [18]. Additionally, interval arithmetic is used for solving the fuzzy eigenvector as well as the fuzzy AHP triangular fuzzy nos. for describing the scaling scheme evolotion in the judgment matrices [18].

The FAHP method's theoretical process is broken down into the following four steps:

Step 1: Comparing the score of performance with the triangular fuzzy nos. $(\tilde{1},\tilde{3},\tilde{5},\tilde{7},\tilde{9})$ for showing how each pair of components in the same hierarchy stacks up against one another

Step 2: Producing a fuzzy judgment matrix $\tilde{A}(aij)$ as depicted underneath by creating the fuzzy comparison matrix utilizing triangular fuzzy numbers and pair-wise comparison;

$$\tilde{A} = \begin{pmatrix} 1 & \widetilde{a_{12}} \dots \dots . \widetilde{a_{1n}} \\ \widetilde{a_{21}} & 1 \dots \dots \quad \widetilde{a_{2n}} \\ \widetilde{a_{31}} & \dots \dots \dots . \widetilde{a_{3n}} \\ \dots & \dots \dots \dots \quad \dots \\ \widetilde{a_{n1}} & \widetilde{a_{n2}} \dots \dots \quad 1 \end{pmatrix}$$

Where, $\widetilde{a_{ij}^{\alpha}} = 1$, if i = j, and $\widetilde{a_{ij}^{\alpha}} = \tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}$ or $\tilde{1}^{-1}, \tilde{3}^{-1}, \tilde{5}^{-1}, \tilde{7}^{-1}, \tilde{9}^{-1}$, if i ≠j

Step 3: Solving the fuzzy eigen value: A fuzzy eigen value ($\tilde{\lambda}$) is a fuzzy number solution to

$$\tilde{A}\tilde{x} = \tilde{\lambda}\tilde{x} \qquad (3)$$

Where is the Fuzzy number (a_ij^α)̃ matrix with n elements? And the fuzzy integer x̃_i. is contained in the non-zero, nxl, fuzzy vector x. Equation Ã x̃ = λ̃ x̃ is equal to the performing fuzzy calculations and supplements utilizing interval arithmetic and - cut.

$$[a_{i1l}^{\alpha}, x_{1l}^{\alpha}, a_{i1u}^{\alpha}, x_{1u}^{\alpha},] \oplus \dots \oplus [a_{inl}^{\alpha}, x_{nl}^{\alpha}, a_{inu}^{\alpha}, x_{nu}^{\alpha},] = [\lambda x_{il}^{\alpha}, \lambda x_{iu}^{\alpha}]$$

Where,

$$\tilde{A} = \lfloor \widetilde{a_{ij}} \rfloor, \ \widetilde{x^{t}} = (\widetilde{x_1}, \dots \dots, \widetilde{x_n})$$

$$\widetilde{a_{ij}}^{\alpha} = [a_{ijl}^{\alpha}, a_{iju}^{u}], \ \widetilde{x_i}^{\alpha} = [x_{il}^{\alpha}, x_{iu}^{\alpha}], \ \tilde{\lambda}^{\alpha} = [\lambda_i^{\alpha}, \lambda_u^{\alpha}]$$

(4)

For 0 < α≤ 1 as well as the whole i, j, where i= 1, 2, …., n, and j= 1, 2, …., n

It's well recognized that the maker of decision maker's or the confidence of expert in her or his preferences or conclusions is incorporated into the cut. The index of optimism measures the satisfaction degree for the judgment matrix (μ). μ (the higher level of optimism) is indicated by an index value that is larger. According to Yong-Han Lee et al. (2003), the optimism index is a linear convex amalgamation and is well-defined as:

$$\widetilde{\alpha_{iju}^{\alpha}} = \mu a_{iju}^{\alpha} + (1 - \mu) a_{iju}^{\alpha}, \forall \mu \in [0, 1] \qquad (5)$$

The subsequent matrix can be determined beyond setting the index of optimism for evaluating the satisfaction level while the α is fixed.

Fixing the value and determining the maximum Eigen value results in the calculation of the Eigen vector, which produces an intermission set of values from a fuzzy no. When α is 0.5m this will result in a set α0.5 (2, 3, 4). And, the procedure is demonstrated utilizing Table 2 and Figure 2.

$$\tilde{A} = \begin{pmatrix} 1 & \widetilde{a_{12}} & \dots & \dots & \widetilde{a_{1n}^{\alpha}} \\ \widetilde{a_{21}^{\alpha}} & 1 & \dots & \dots & \widetilde{a_{2n}^{\alpha}} \\ \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \\ \widetilde{a_{n1}^{\alpha}} & \widetilde{a_{n2}^{\alpha}} & \dots & \dots & 1 \end{pmatrix}$$

Step 4: Prior to determining the maximum, the pairwise comparisons matrix must be normalized, the priority weights (approximate attribute weights), and the matrices as well as the precedence weights for the substitutes must be calculated. And, the consistency ratio (CR) for the formulated matrices and the overall consistency index must be calculated using the following equation in order to verify that the findings of the FAHP approach are adequate. The consistency index is referred to as the (CI).

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{6}$$

The consistency ratio (CR) is used to estimate directly the consistency of pair wise comparisons. The CR is computed by dividing the CI by a value obtained from a Random index (RI) table in Table 2.

Table 2: Random index table

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

$$CR = \frac{CI}{RI} \tag{7}$$

If the (CR) is less than 0.10, then the formulated decision matrix is acceptable, otherwise not. The most well-known method for resolving MCDM issues is called "Technique for Order Performance by Similarity to Ideal Solution (TOPSIS)", which being put forth via Hwang and Yoon [19]. This approach is predicated on the idea that the selected substitute has to be nearest to the "Positive Ideal Solution (PIS)", or the solution that minimizes the costs and maximizes the benefits, and the furthest from the "Negative Ideal Solution (NIS)".

Chen [21] elongated the (TOPSIS) with triangular (FNs), and presented a vertex technique for calculating the space between (2) triangular (FNs). When $\tilde{x} = (a_1, b_1, c_1), \tilde{y} = (a_2, b_2, c_2)$ are (2) triangular (FNs), thus

$$d(\tilde{x}, \tilde{y}) := \sqrt{\frac{1}{3}[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2]}. \tag{11}$$

Experimental Procedure

In this work, the hardness of the samples was measured using a Microhardness Vickers device, and then the samples were coated with titanium oxide TiO2 in the form of powder using the Pulse Laser Deposition method within different variables, such as voltage and number of pulses, where the surface of the sample was completely coated. After that, the samples were heated for annealing at a temperature of 300ºC to increase the cohesion and homogeneity of the film on the surface of the sample, and finally the hardness was measured again to see the difference.

Agar diffusion technique was employed for determining the antibacterial action of TiO2 thin film. Escherichia coli suspensions being obtained from the 18-hour nutritional broth cultures and then they were diluted (1:10) to the appropriate bacterial density (1.5 * 10-8 CFU/mL) and corrected to (0.5) McFarland standard turbidity (1.5 * 10-8 CFU/mL). Then, (0.1 mL) of the bacterial suspensions (1.5 * 10-6 CFU/mL) were added to the Mueller-Hinton agar medium as an inoculant. Bacterial suspensions (50 L) dispersed on the surface of a 12 cm petri plate with Muller-Hinton agar were employed to assess the antibacterial activity of nanoparticles. The labeled thin sheets of TiO2 in various concentrations (1, 2, 3, 4, 5, 6, 7 and 8) were placed on the agar's surface and let to set for 5 minutes. After that, the substrate containing various concentrations of the tested technique was added, and it was left to set for 15 minutes. The inhibition zone around the discs was measured using a micrometer after the plates had been incubated for (18 hr) at (37ºC). The inhibition regions have in fact demonstrated the antibacterial properties of nanoparticles. The antibacterial activity of nanoparticles increases with the diameter of the inhibitory region.

3. Results and Discussion

Utilizing the agar plate method, the produced TiO2 thin film's antibacterial properties were evaluated (R1). Gram-negative bacteria (Escherichia coli) were used to test the antibacterial activity (R2). Evaluation has been done on the calculated activity of the TiO2 thin film and the difference in diameter zone. For all samples, the antibacterial activity displayed the inhibition zone at various values. It exhibited the 3 mm reduction area with samples 1, 4,5 and 6, the 4 mm reduction area with samples 3, 8 the 5 mm reduction area with sample (7), and the 2 mm reduction area with sample (2). Taking into account the variability caused by the voltage, the quantity of pulses, and the separation between the target and substrate, it was found that the diameter zone and activity of the TiO2 thin film increased for samples 1, 3, and 5 and decreased for samples (2, 4, 6, 7, and 8). It was discovered by measuring the reduction area that the low concentrations of 600 pulses and a distance of 3 cm had an impact on E. coli, and that the effect grew with the greater concentrations of 900 pulses and a 3 cm distance. And, the results manifested that a potent thin film is produced which performs better at inhibiting the bacterial existence when the number of pulses is increased and the space between the substrate and the target is decreased. The findings of the present study demonstrated that the TiO2 thin films have a potential antibacterial action against the specified bacteria (R3). Furthermore, it strengthens the possibility of using TiO2 thin films as antibacterial agents against clinically relevant bacterial strains. Other technological variations with comparable concentrations will be tested for the foreseeable future.

The orthogonal array of Taguchi-approach for the PLD results is shown in Table 3

Table. 3 orthogonal array with PLD process paramrters for PLD

Voltage (v)	No. of pulse	Distance (cm)	Microhardness Vickers (HV)	Biological Results
600	600	3	382.3	1
600	600	5	359.05	2

600	900	3	460.7	3
600	900	5	535.85	4
900	600	3	569.25	5
900	600	5	595.4	6
900	900	3	523.85	7
900	900	5	545.4	8

Throughout the PLD method optimization, the optimized parameters are voltage, No. of pulse, and distance. The parameters that are being measured are microhardness and biological results. During the analysis, only the target parameters are analyzed.

In the present investigation, AHP as well as TOPSIS based Taguchi-approach was implemented to the PLD data. The maximized objectives are microhardness and biological results. Then, Table 3 is subjected to normalization. According to the intended action, Equation (11) was employed for the normalization process. Table (4) displays the normalized values that were obtained.

Table (4): Normalized Parameters Values

Normalized Hardness	Normalized Bio-results
0.09837106	0
0	0.166666667
0.430082505	0.4
0.748043156	0.75
0.889359001	1.333333333
1	2.5
0.697270996	6
0.788449334	1

Now, the weights are determined using fuzzy linguistic variables that are defined utilizing Taguchi Analysis results. Figure 1 depicts graphically the fuzzy linguistic parameters defined and listed in the Table 4, and Table 5 displays the pairwise comparison matrix for the responses. The similar matrix in terms of the triangular fuzzy nos. is given in the Table 5.

Table 5 : Pairwise comparison matrix for responses in terms of linguistic parameters

Priorities	Microhardnes	Biological Results
Microhardnes	1	HV
Biological Results	HV	1

Table (6) Pairwise comparison matrix for responses in terms of Triangle Fuzzy Numbers

Priorities	Microhardnes	Biological Results
Microhardnes	(1,1,1)	(0.7,0.9,1)

Geometric aggregation is then carried out on table 6. Equation 2 is used for geometric aggregation. Table 7 shows the aggregated values for various properties. Best non-Fuzzy Performance (BNP) value is then calculated using (3). Weight for each ith parameter is then computed using expression (4). Calculated BNP values and weights of various parameters are given in table 8.

$$GA = \left(l_{ij} = \prod_{j=1}^{k} l_{ij},\ m_{ij} = \prod_{j=1}^{k} m_{ij},\ u_{ij} = \prod_{j=1}^{k} u_{ij} \right) \text{ where } i = 1 \ldots n \quad (2)$$

$$BNP = \frac{[(c-a)+b-a]}{3} + a \quad (3)$$

Table (7): GA values for various properties

Priorities	GA Values		
Microhardnes	0.7	0.9	1
Biological Results	1	1.111	1.429

Table (8):Weight values of various properties

Criteria	BNP values	Weight	%
Microhardnes	1.566666667	0.418149466	42%
Biological Results	2.18	0.581850534	58%
		1	100%

Table Weighted Normalized Values		
Weighted Normalized Microhardness	Weighted Normalized Biological Results	
160.566	0.58	
150.801	1.16	
193.494	1.74	
225.057	2.32	
239.085	2.9	
250.068	3.48	
220.017	4.06	
229.068	4.64	

Using the weights calculated, weighted normalized parameters are computed. Weighted normalized parameter value is the product of weight of the parameter and parameter value. Table 9 shows the weighted normalized values.

The technique Fuzzy being currently utilized for selecting the optimum value from such weighted normalized matrix as stated in Ref. [10]. The Positive-ideal solution (A) as well as the Negative-ideal solution (A-) for every variable of the weighted normalized matrix in the Table 8 is computed utilizing equations (5) and (6).

$$A^{+}\ \begin{cases} \{\tilde{v}_1^{+}, \tilde{v}_2^{+}, \tilde{v}_3^{+}, \ldots, \tilde{v}_n^{+}\} = \{(\max_i v_{ij} \mid i = 1..m, j = 1..n)\} & \text{for Maximization} \\ \{\tilde{v}_1^{+}, \tilde{v}_2^{+}, \tilde{v}_3^{+}, \ldots, \tilde{v}_n^{+}\} = \{(\min_i v_{ij} \mid i = 1..m, j = 1..n)\} & \text{for Minimization} \end{cases} \qquad (5)$$

$$A^{-} = \begin{cases} \{v^{-}, v^{-}, v^{-}, \ldots\ v^{-}\} = \{(\max_i v_{ij} \mid i=1\ldots m, j=1\ldots n)\} & \text{for Minimization} \\ \{v^{-}, v^{-} v^{-}, \ldots\ v^{-}\} = \{(\min_i v_{ij} \mid i=1\ldots m, j=1\ldots n)\} & \text{for Minimization} \end{cases} \qquad (6)$$

The resulted values are evinced in the Table 10. Currently, the every substitute distance is calculated from both A+ as well as A- utilizing equation (7).

$$\text{Distance from } A^{+}, S^{+} = \sqrt{\sum_{j=1}^{m} (v_{ij} - v_i^{+})^2}, \quad i = 1\ldots\ldots n \qquad (7)$$

$$\text{Distance from } A^{-}, S^{-} = \sqrt{\sum_{j=1}} \quad , i=1\ldots\ldots\ldots n$$

Table (8) distance of each alternative and closeness coefficient

Weighted Normalized matrix of TOPSIS	
0.268661241	0.070014004
0.261953085	0.140372481
0.348275729	0.212664362
0.432142447	0.2901905
0.509065714	0.379033151
0.618605519	0.491418545
0.692713955	0.657900584
0.999995723	0.996441612

S_i^{+}	S_i^{-}	Pi
1.180304299	0.006708155	0.006
0.070358477	0.297193291	0.809
0.408071212	0.408071212	0.500
0.520535898	0.520535898	0.500
0.63467632	0.63467632	0.500
0.790041122	0.790041122	0.500
0.955345906	0.955345906	0.500

1.411696615	1.411696615	0.500

Table (9) the positive ideal best (A^+) and the negative ideal worst value (A^-)

0.999995723	0996441612
0.261953085	0.070014004

Table (10): Weighted Normalized matrix of TOPSIS	
0.268661241	0.070014004
0.261953085	0.140372481
0.348275729	0.212664362
0.432142447	0.2901905
0.509065714	0.379033151
0.618605519	0.491418545
0.692713955	0.657900584
0.999995723	0.996441612

After determining the distances, the Closeness Coefficient (CC) or proximity to the perfect solution is calculated utilizing the following equation (8). Then, the alternatives are sorted by this similarity ratio in decreasing order. In TOPSIS, the best solution is the one with rank 1 [10]. Table 11 provides a summary of the derived data.

$$CC_i = S_i^- / S_i^- + S_i^+ \quad (8)$$

Table. 11 TOPSIS applied on weighted averaged matrix

Experimental No.1	Distance from S^+	Distance from S^-	Closeness coefficient CC_i	Rank
1	1.18030	0.00671	0.00565	8
2	0.07036	0.029719	0.80858	2
3	0.40807	0.40807	0.51000	3
4	0.52054	0.52054	0.50000	4
5	0.63468	0.63468	0.42111	6
6	0.79004	0.79004	0.50000	5
7	0.95535	0.95535	0.11110	7
8	1.41170	1.41170	0.81333	1

From the data overhead, it can be noticed that 8th experiment is the optimum solution.

Factors of the (L8) experiment are voltage (900 V), No. of Pulse (900) and Distance (5 cm). The target parameters are microhardness (545.4 HV) and excellent biological results (8).

Conclusions

For the parameter optimization issues in Steel-based PLD (pulsed laser deposition), multi-criteria decision making methods of Fuzzy AHP and Fuzzy TOPSIS-based Taguchi approach were merged in this study. The following is a summary of the findings of the current work:

The Taguchi technique is useful for carefully planning tests.

Using information gathered from Taguchi design studies, fuzzy-AHP can be used to order the results. The results are no longer affected by aleatory uncertainty thanks to the adoption of fuzzy methodology. Fuzzy-TOPSIS can incorporate the weights determined by Fuzzy -AHP.

The ideal parameters for steel-based PLD (pulsed laser deposition) are voltage (900 V), number of pulses (900), and distance (5 cm), and the target parameters are microhardness (545.4 HV) and excellent biological results for the range of PLD (pulsed laser deposition) process parameters that have been taken into consideration.

The Taguchi, Fuzzy AHP, and Fuzzy TOPSIS integrated technique that has been developed can be expanded for use with various pulsed laser deposition settings.

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