

# SELECTION OF TRIBOLOGICAL PLASMA SPRAYED COATINGS USING MULTI-CRITERIA DECISION-MAKING METHODS

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**Abstract:** Decision making methods have been examined within the context of conflicting criteria. Mechanical properties of a number of plasma sprayed coatings based on the modified alumina powder have been given for the purpose of comparative analysis. The modification has been performed by two different methods: 1) by cladding the alumina powder with Ti and Al metal sheaths where the PVD method has been employed; 2) by mechanochemical processing inside planetary ball mill with the titanium oxide nanopowder added. For coating selection, weighed characteristics technique has been used in conjunction with the digital logic and the proposed improved approach to the linear and non-linear data normalization. A conclusion has been made that the most effective, as far as the wear resistance parameter is concerned, are the coatings obtained as a result of the clad alumina powder spraying.

**Keywords:** DECISION-MAKING THEORY, SELECTION OF MATERIALS, PLASMA SPRAYED COATING, CLAD POWDER, NANOPOWDER.

## 1. Introduction

The proper coating material selection is an important and complicated part of the engineering procedure used in manufacturing the wear-resistant parts for the machinery and equipment [1–3]. The choice of the most effective coating material is an important theoretical and practical problem that has to be solved through a systemic and most rational approach at the research stage. Wrong selection of material can lead not only to undesirable consequences, but also to considerable material losses.

The strength characteristics and tribological properties of plasma sprayed coatings can be improved through the use of nanodisperse modifiers that are bonded with the original powder before spraying [4]. Usually, the modifier functions are performed by ultrafine components that ensure the formation inside the coating of a certain structure that is characteristic of solid and wear-resistant materials. In the process, simple oxide based chemical compounds of the  $Me_2O_3$  (Me – Al, Cr) and  $MeO_2$  (Me – Ti, Zr, Si) types can be used, as well as the highly chemically active pure metals. In practice, it is advisable to modify the powders with conglomeration with the help of mechanochemical synthesis procedure, or by cladding the powder particles with the use of physical vacuum deposition (PVD) methods.

The alumina based wear-resistant coatings are widely used in various branches of engineering [5]. The plasma spraying technique of wear-resistant ceramic coatings is characterized by a medium relative cost price value in comparison with other wear-resistant coating techniques. Currently, no studies exist in the field of analysis and application of the decision making methods related to the selection of the plasma sprayed coatings. At the same time, great many material selection approaches for various structural components are available [1, 6–8]. The multicriterion methods of the material selection that are currently in use can be adapted to the procedure of plasma sprayed coating selection, too. The weighted characteristics method in conjunction with the non-linear data normalization approach and modified digital logic method can also be applied to the coatings [9].

The cladding of the powder particles by PVD methods is a potentially profitable area of composite powders production. Some of the results obtained in the process Cu, Ti and Pt nano-films by magnetron sputtering on the powders are given in paper [10]. Although the quality of the obtained powders is high enough, this technique, nevertheless, is characterized by relatively low film deposition velocity which significantly increases the cladding time. Therefore, the vacuum arc evaporation technique has proven more effective in obtaining thin quality films of the ceramic powders.

Lately, many scientific works have appeared where the issues of spraying powder modification with nanoparticles have been examined. The issues of powder processing with mechanochemical synthesis procedure have been studied in papers [4, 11]. The possibility of searching for effective modifiers for obtaining composite coatings with antifriction characteristics has been studied in paper [4]. After analyzing the ultrafine oxides with the structures of corundum and rutile, carbon and boron nitride, as well as the metals with the structures of the tungsten and magnesium type, a conclusion has been made in favor of the effectiveness of using the oxide aluminum as a modifier. Selection, adaptation and substantiation of the multicriterion decision making method as used in the process of the best wear-resistant coating selection.

## 2. Materials and methods

Alumina powders of the 40–63  $\mu\text{m}$  fractions and of the following three modifications have been used for plasma sprayed coating:

- 1) alumina powder in its initial state;
- 2) alumina powder cladding with Ti and Al metal sheaths by PVD method;
- 3) alumina powder modified with nano- $\text{TiO}_2$  powder (with the 40–50 nm fraction) in the amount of 1.5%.

The sheaths made of alumina powder particles consisted of the Ti sublayer 70–160 nm thick and of the top Al layer 2–3  $\mu\text{m}$  thick. Hereinafter the clad powder is referred to as  $\text{Al}_2\text{O}_3/\text{Ti}/\text{Al}$ . The cladding process was performed at the PVD equipment with specially developed vibration powder mixing device. The technological processes occurring during the cladding powder by PVD method are described in detail in paper [12].

The alumina powder has been modified with nano- $\text{TiO}_2$  by mechanochemical processing inside the XQM-2 planetary ball mill in a vacuum [13]. Such treatment facilitated the formation of strength bonds between the micro- and nanoparticles of the powder composition, which provided for the nanoparticles transfer into the coating during subsequent plasma spraying.

The powders were sprayed by plasma torch with partially superimposed arc and an additional plasma jet blow-off with concentric shielding gas flow. The arc current has been chosen within the range of 80–90 A, the voltage – within the 50–60 V range; the plasma-forming and shielding gas (argon) flow rate would amount to 2–3 L/min at the nozzle with the diameter of 2 mm. Due to such design specifics and process conditions, the plasma jet flow mode was close to laminar which also provided for favorable conditions for the save and transfer into the coating of

both the cladding metal sheaths and the nanoparticles. The 200–300  $\mu\text{m}$  thick coating was sprayed onto flat  $5 \times 10 \times 20 \text{ mm}^3$  specimens (St 37 low carbon steel).

The NiAl bond coat was sprayed onto steel substrate, to improve adhesion strength of the ceramic coating. The bond coat thickness was 100–150  $\mu\text{m}$ .

The coating materials were chosen based on the following criteria:

- wear resistance,
- adhesion strength,
- microhardness,
- residual stress.

The tensile adhesion tests were used for the adhesion strength evaluation, in accordance with ASTM C633. The microhardness was evaluated by forcing in the Vickers pyramidal diamond indenter at the 0.98 N load at the PMT–3 device. Tribological tests were performed with the help of SMTs–2 friction machines in a “block-on-disc” wear test configuration. The rotation disk speed was 330 rpm with the applied load of 55 N. While evaluating the comparative wear resistance of the coatings obtained from cladded and modified powders, the pure alumina coating was used as the benchmark. To evaluate residual stress, low-carbon steel samples sized  $0.2 \times 9 \times 85 \text{ mm}^3$  were used that were subjected to abrasive jet machining on both sides and rigidly attached to a flat surface to guarantee the impossibility of deforming during the spraying process. The residual stress was evaluated by the changes in the sample's radius of curvature after the spraying [14]. The elastic modulus plasma of the plasma sprayed coatings was determined after the tensile testing of coated flat specimens based on the technique [15]. The fracture strength of the coating was evaluated based on the [16] technique. The test results are given in Table 1.

**Table 1. Mechanical properties of the plasma sprayed coatings**

Code	Coating material	Parameters				
		1	2	3	4	5
		Adhesion strength, MPa	Residual stress, MPa	Microhardness, GPa	Comparative wear resistance	Fracture strength, $\text{MPa} \cdot \text{m}^{1/2}$
1	$\text{Al}_2\text{O}_3$	6	–26	9.7	1	2.0
2	$\text{Al}_2\text{O}_3$ / bond coat NiAl	21	–19	9.5	1	2.0
3	$\text{Al}_2\text{O}_3$ /Ti/Al	37	–17	11.3	6.3	2.4
4	$\text{Al}_2\text{O}_3$ /Ti/Al/ bond coat NiAl	41	–12	11.3	6.3	2.4
5	$\text{Al}_2\text{O}_3$ - 1.5% nano $\text{TiO}_2$	11	–21	10.1	4.2	2.3

### 3. Method for the tribological coating material selection

The parameters of comparative wear resistance (1) and adhesion strength (3) are prioritized for the wear-resistant coatings; the wear resistance (1) parameter is considered to be the most important of them. The residual stress parameter (5) ranks as the third in the order of importance. The comparative wear resistance and fracture strength parameters are of the least priority. Therefore, when choosing an optimum coating composition option, the values

of parameters 1, 3, 4 and 5 should be maximized, and the value of parameter 2 – minimized.

The material selection process involved the use of known decision making methods. Determination of the production requirements is the first step of the selection process. The wear resistance of the coating constitutes the main requirement. The obtained earlier values of the mechanical properties have been used in the process of coating selection (see Table 1). Such properties as the comparative wear resistance, microhardness and adhesion strength are the beneficial ones; the residual stress – non-beneficial ones, accordingly. Since the properties are set in numerical form, the material selection method based on determining the weighted characteristics method has been used [4].

*Weighted characteristics method.* The method allows the coating material ranking based on the efficiency indexes. The efficiency index  $\gamma$  is determined as follows:

$$\gamma = \sum_{i=1}^n Y_i \alpha_i \quad (1)$$

where  $Y$  is the normalized value of the  $i$ -th coating characteristic;  $\alpha$  is the weighting factor;  $n$  is the total number of coating options.

The coating characterized by the highest efficiency index is the best one for practical purposes. The weighting factor  $\alpha$  has been determined with the use of digital logic methods to compare the importance of properties. When comparing properties that use different units of measurement, a normalization procedure is performed which can be both linear and non-linear.

*Digital logic approach.* Experts evaluate the importance of the properties by their pairwise comparison. The most important characteristic is assigned the value of “1” and the least important – the value of “0”. The total number of possible solutions  $N$  is determined by the following formula:  $N = n(n-1)/2$ , where  $n$  is the number of properties being compared. The weighting factor  $\alpha$  for each of the properties is determined by the relation between the number of positive solutions and the total number of possible solutions  $N$ . The sum of all the weighting factors equals to one ( $\sum \alpha = 1$ ). The weighting factor  $\alpha$  is determined by the following formula:

$$\alpha = N_{\text{positive}} / N \quad (2)$$

where  $N_{\text{positive}}$  is the number of positive solutions.

*Linear data normalization.* Let's normalize the values of the properties so that the maximum value would not exceed 100. For the beneficial properties, this is the ratio between the value of the  $X$  characteristic and the maximum value  $X_{\text{max}}$  of this characteristic multiplied by 100:

$$Y = (X / X_{\text{max}}) \cdot 100 \quad (3)$$

For a non-beneficial characteristic, this is the ratio between the minimum value of the  $X_{\text{min}}$  characteristic and the current value of this characteristic multiplied by 100:

$$Y = (X_{\text{min}} / X) \cdot 100 \quad (4)$$

*Modified digital logic.* The shortcomings of the digital logic technique lie in the fact that the least important characteristic is assigned the value of “0”. Consequently, its weighting factor will be equal to zero. Therefore, this characteristic is excluded from the process of coating material selection. The modified technique proposes assigning the values of “1” to the least important characteristic, the value of “3” – to the most important characteristic, and the value of “2” – to the properties that are

equally important. Compared with the digital logic approach, the calculation method will differ in determining the number of possible solutions:

$$N = (n - 1) / 2$$

*Non-linear data normalization.* This method uses non-linear function while transforming the values of the beneficial and non-beneficial properties, respectively:

$$Y = a_1 \ln(b_1 X + c_1) \quad (5)$$

$$Y = a_2 \ln(b_2 / X + c_2) \quad (6)$$

where  $a_1, a_2, b_1, b_2, c_1$  and  $c_2$  are constants.

Determination of the above constants is necessary for a non-linear normalization. When performing calculations based on expression (5), it is necessary to take into account the following boundary conditions: 1)  $Y = -100$  (at  $X = 0$ ); 2)  $Y = +100$  (at  $X = X_{max}$ ).

The critical value parameter for a considered  $X_k$  characteristic allows an expert to assign the boundary value below which the normalized value  $Y$  becomes negative and the efficiency index  $\gamma$  is lowered. The third boundary condition is of the form  $Y = 0$  (at  $X = X_k$ ). The fulfillment of the three conditions allows calculating constants based on the following expressions:

$$\begin{aligned} a_1 &= -100 / \ln(X_k / (X_{max} - X_k)) \quad ; \\ b_1 &= (X_{max} - 2X_k) / X_k (X_{max} - X_k) \quad ; \\ c_1 &= X_k / (X_{max} - X_k) \quad ; \end{aligned} \quad (7)$$

According to the proposed expressions (7), the characteristic's normalization function is indeterminate at  $X = X_{max} / 2$ . With this condition taken into account, the function has the following form:  $Y = (200X / X_{max}) - 100$ . The final relations in this case are as follows:

$$\begin{aligned} Y &= a_1 \ln(b_1 X + c_1) \quad , \\ \text{at } X_k &\neq X_{max} / 2 \quad ; \\ Y &= (200X / X_{max}) - 100 \quad , \\ \text{at } X_k &= X_{max} / 2 \quad ; \end{aligned} \quad (8)$$

Similar approach can be used in relation to the non-beneficial properties, too. The boundary conditions have the following form: 1)  $Y = +100$  (at  $X = X_{min}$ ); 2)  $Y = -100$  (at  $X \rightarrow \infty$ ).

The critical value for the characteristic is the value of  $X = X_k$  (at  $Y = 0$ ). The necessary constants are calculated based on the following expressions:

$$\begin{aligned} a_2 &= -100 / \ln(-X_k / (X_{min} - X_k)) \quad ; \\ b_2 &= -X_k^2 + 2X_{min} X_k / X_{min} - X_k \quad ; \\ c_2 &= -X_{min} / (X_{min} - X_k) \quad ; \end{aligned} \quad (9)$$

In common with the previous case, the same procedure should be performed for determining the form of the norming function at  $X = 2X_{min}$ . With this condition taken into account, the function has the following form:  $Y = (200X_{min} / X_{max}) - 100$ .

The final relations in this case are as follows:

$$\left\{ \begin{aligned} Y &= a_2 \ln\left(\frac{b_2}{X} + c_2\right) \text{ at } X_k \neq 2X_{min} \\ Y &= \frac{200X_{min}}{X_{max}} - 100 \text{ at } X_k = 2X_{min} \end{aligned} \right\} \quad , \quad (10)$$

Experts have determined the critical values  $X_k$  of the coating properties (see Table 2).

**Table 2.** Critical values of the coating properties  $X_k$  for the improved non-linear normalization approach

Critical value of the parameters	Adhesion strength, MPa	Residual stress, MPa	Microhardness, GPa	Comparative wear resistance	Fracture strength, MPa·m <sup>1/2</sup>
$X_k$	6	86	1.0	3.0	2.1

*Improvement of the linear and non-linear parameter normalization technique.* Residual stress values in the studied coatings vary from -26 MPa to -12 MPa (see Table 1). It would be incorrect to apply any of the above-mentioned normalization techniques on an "as is" basis. That's why it is necessary to improve both parameter normalization methods. Let's make a proportional linear transformation of the data into the positive value area; at the same time, let's start the  $X_{min}$  readout from the value of 10. The similar transformation should be carried out for the critical residual stress values  $X_k$  defined previously by the experts (see Table 3).

**Table 3.** Values of the residual stress for performing calculations employing the improved linear and non-linear normalization

Initial values of the residual stress, MPa	-12	-17	-19	-21	-26
Transformed values of the residual stress $X$	10	15	17	20	25

*Comparison of coating properties.* Let's apply the above methods while comparing the coating properties. The results obtained by the digital logic approach and the weighting factors  $\alpha$  calculated by formula (2) are given in Table 4.

**Table 4.** Determination of the weighting factors related to coating properties (by digital logic approach)

No	Parameters	Number of possible solutions									$N_{positive}$	Weighting factors, $\alpha$
		1	2	3	4	5	6	7	8	9		
1	Comparative wear resistance	1	1	1	1						4	0.44
2	Microhardness	0			1	1	1				3	0.33
3	Adhesion strength		0		0			1			1	0.11
4	Residual stress			0		0			0	0	0	0
5	Fracture strength				1			0	0	1	2	0.11

The results obtained by improved non-linear normalization (Table 5), technique (using specified formulas) and the efficiency index  $\gamma$  calculation (by the above formula (4), (5)) are given in Table 6. Data have been used to normalize the residual stress. The results obtained by the modified digital logic method (with expert participation) are given in Table 7. Also, this table shows the results of the weighting factors  $\alpha$  calculation by formula (2).

**Table 5.** Calculation for the linear normalization

Code	Adhesion strength	Residual stress	Microhardness	Comparative wear resistance	Fracture strength
1	14.63	100.0	85.84	15.87	83.33
2	51.22	141.18	84.07	15.87	83.33
3	90.24	160.0	100.0	100	100.0
4	100.0	240.0	100.0	100	100.0
5	26.83	126.32	89.38	66.67	95.83

**Table 6.** Calculation results for the linear normalization  $Y$  parameters and the  $\gamma$  efficiency index

Code	Adhesion strength	Residual stress	Microhardness	Comparative wear resistance	Fracture strength	$\gamma$ efficiency index
1	11.62	0	28.61	7.05	9.26	46.55
2	5.69	0	28.02	7.05	9.26	50.03
3	10.02	0	33.33	44.44	11.11	98.92
4	11.11	0	33.33	44.44	11.11	100.0
5	2.98	0	27.79	29.63	10.67	73.05

**Table 7.** Determination of the weighting factors for coating properties (by modified digital logic method)

Parameters	Number of possible solutions $N = n(n-1)/2$									$N_{\text{positive}}$	Weighting factors, $\alpha$
	1	2	3	4	5	6	7	8	9		
1 Comparative wear resistance	3	3	3	2						11	0.31
2 Microhardness	1			3	3	3				10	0.28
3 Adhesion strength		1		1			3			5	0.14
4 Residual stress			1		1			1		3	0.08
5 Fracture strength				2			1	1	3	7	0.19

The values of constants have been calculated  $a_1, a_2, b_1, b_2, c_1, c_2$ , by formulas (7) and (9), based on the improved non-linear data normalization technique. The non-linear normalization (Table 8) of the coating properties has been performed  $Y$  by formulas (8) and (10) where the converted Table 3 data and the critical  $X_k$  Table 2 data values have been used. Also, the efficiency index  $\gamma$  has been calculated by formula (1). The calculation results are given in Table 9.

**Table 8.** Calculation for the non-linear normalization

Code	Adhesion strength	Residual stress	Microhardness	Comparative wear resistance	Fracture strength
1	392.54	-290.0	293.1	244.93	-96.08
2	463.57	-381.8	292.2	244.93	-96.08
3	495.68	-416.0	299.6	1148.50	-95.26
4	501.5	-529.6	299.6	1148.50	-95.26
5	426.91	-351.8	294.8	871.65	-95.46

**Table 9.** Non-linear normalization  $Y$  parameters and the  $\gamma$  efficiency index parameters

Code	Adhesion strength	Residual stress	Microhardness	Comparative wear resistance	Fracture strength	$\gamma$ efficiency index
1	54.52	-24.17	81.4	68.73	0.39	180.87
2	64.38	-31.82	81.16	68.73	0.39	182.84
3	68.84	-34.67	83.22	350.93	0.47	468.79
4	69.65	-44.14	24.97	350.93	0.47	401.89
5	59.29	-29.31	81.88	266.34	0.45	378.65

#### 4. Conclusion

The specifics of the coating material selection task demonstrate the necessity of multicriterion optimization methods. Only material among the investigated coating variants can successfully compete with one another:  $\text{Al}_2\text{O}_3/\text{Ti}/\text{Al}$  (code 3) and  $\text{Al}_2\text{O}_3/\text{Ti}/\text{Al}$  with bond coat NiAl (code 4). Based on the analysis of the efficiency index values, one can come to a conclusion that the plasma sprayed coating based on the clad powder has the best properties. At the same time, the alumina ceramic coating, according to the improved non-linear normalization technique, is the least effective. The stated method is characterized by a number of advantages, including the wider gradation of the efficiency index values distribution since the critical values of the coating properties are used that have been determined by experts.

The existing decision making methods can be adapted and improved for their use while selecting the materials for the wear-resistant coatings. The weighted characteristics technique, in conjunction with the improved non-linear data normalization and the modified digital logic approach as applied to coating properties, constitute the optimal and systemic approach.

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