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FMEA QUALITY IMPROVEMENT METHOD OF FLAME SPRAYING THERMAL INSULATION

Abstract: *FMEA is a very popular and effective analysis. The main advantage is the arrangemnet of expert groups, which define risks, their effects and organize corrective and preventive actions. But such analysis also has some disadvantage, first of all it is the uncertainties, the other one is the need to choose the corrective event among those that have been suggested. Besides, a typical model for assessing the risks of potential failures of the coating applied by the method of gas-thermal plasma spraying on the blades of a gas turbine of a gas turbine engine has been developed. The model is based on the Design Failure Mode and Effect Analysis. The structural and functional analysis of the coating design was carried out. The failures resulting from the failure of the coating to perform the function are determined. The potential causes and consequences of failures have been identified. An assessment of the risks of failures was carried out and the priority of actions for their elimination was established. Measures to improve the quality of the coating applied by the method of gas-thermal plasma spraying are described.*

Keywords: *FMEA; Corrective actions; Turbine blades.*

1. Introduction

To improve the quality and economic efficiency of gas turbine engines, it is necessary to increase the durability of their component parts. The weakest structural elements of a gas turbine engine, as a rule, are the blades of a gas turbine. The working surfaces of the turbine blades are subjected to intense wear and destruction from exposure to high and variable temperatures. Increasing the service life, reliability and quality of turbine blades is possible due to the application of special protective coatings on the surface of parts by gas-thermal plasma spraying.

To improve the quality of coatings applied by gas-thermal plasma spraying and to prevent the occurrence of risks of coating defects, a Failure Mode and Effects Analysis was applied (FMEA). The article presents the Design Failure Mode and Effect Analysis of a heat-protective coating applied to the blades of a gas turbine by gas-thermal plasma spraying (DFMEA).

2. FMEA under uncertainty

FMEA is known to be aimed to evaluate potential systems, products or process failures. A statistic-expert method is used to evaluate the system. As a statistic evaluation method we most often use the analysis of potential failure, reason and effect. (Zhang et al., 2015) And as an expert evaluation method we use the analysis of significance of failure and effect or the reason and also the possibility of potential failures and

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effects, which depends on the risk evaluation model.

According to scientific theories, there are the following types of uncertainties of FMEA:

- Environmental uncertainty (1st type). It is estimated by the relationship of the amount of system information and the confidence level in the accuracy of this information, which means the system information quantity and quality relationship (Li et al., 2015).
- Decision-making uncertainty (2nd type). It is described by the probability of the decision made. According to FMEA results, some corrective actions are being developed, the probability of which is other than unity (Singh Chauhan et al., 2017).
- The decision effect uncertainty (3d type). The state of the system is dynamic and the implementation of the approved event will lead to the change of the FMEA as a whole, as the risk evaluation will change (Liu et al., 2016). Besides, when the risk priority number is calculated, there is very often a need to check the analysis again, because the discrepancy appears between the experts evaluation of both effect significance and the general risk model in the system and calculation results, which is the decision effect uncertainty of points mentioned in FMEA tables and charts (Kozlovskiy et al., 2014).
- Variation uncertainty (4th type). Variation uncertainty is a change of parameters and system operation conditions – a new quasi-conditions uncertainty, in other words it is variability (Jin et al., 2015). A system changes during FMEA, the data collection itself changes. In fact, FMEA is expected for the stationary system analysis and it is important to take into account this disadvantage (Toroptsev et al., 2019).

2.1 Uncertainties during FMEA

Uncertainty as the information measure. It is informational entropy known by research of Hartley, Shannon and others. In our case it shows unpredictability of any risk or its factors, and also any specific effect, because there are systems, where risks or its factors can lead to several effects with a certain share of probability.

Uncertainty as the level of awareness. It describes the state of uncertainty, when there is a gap between the real level of awareness (knowledge about the system) and the system itself (Lee et al., 2015). A solution to this problem during FMEA is known to be in finding a professional team of experts that can characterize the behavior of a system at each stage of a life cycle (Facchinetti & Osmetti, 2018).

Uncertainty as a need of choice. The main problem of this type of uncertainty is that it is quite difficult to set specific characteristics of corrective actions efficiency (Wang et al., 2015). Thus, there is a need to design such a FMEA procedure that considers alternative options of corrective actions.

Uncertainty of a data quality. Data quality consists of the following characteristics:

- reliability,
- accuracy,
- information exhaustiveness,
- value,
- data relevance,
- information clarity.

The evaluation of information by uncertainty is based on data relevance and accuracy, its exhaustiveness and clarity (Panyukov & Kozlovskiy, 2014). Besides, data quality in this case can be shown by information asymmetry, which means the information about system is distributed irregular among experts, which is acceptable (Du et al., 2016).

If information asymmetry leads to the professional dialogue and corrective actions, then "expert failure balance" (a situation when experts equally use inaccurate, non-exhaustive, unreliable information or intelligent database) leads to non-effective solutions and as a result FMEA appears to be unreasonable. (Zharov &Kozlov, 2018)

Uncertainty as a source of risk. Risk depends on uncertainty, which means when the uncertainty increases, the risk increases as well (Franceschini & Maisano, 2015). The increase value will change and it depends on such a concept as "risk elasticity". Uncertainty can be a direct source of risk.

Uncertainty as an ambiguousness of events. The decision is taken in conditions of uncertainty; it is not possible to estimate the probability of potential results (Liu et al., 2019).

Uncertainty as a management tool and the tool of system stability. One of system uncertainty is its self-organization. In that case, when the vector of self-organization is co-directed with the general development vector, the level of system management is high (Kartashevskii et al., 2015). In other case, when the vectors are discrepant (for example, individuals that are interested in siphoning off gas appear in the system), then the system is suddenly out of control.

2.2 The method of approximation FMEA results to single-objective task of arranging corrective actions.

As a result of cooperation with the expert group during FMEA a number of alternative corrective actions appears, so there is a need to make a choice. (Zhu et al., 2018)

The costs of each alternative are known. And there is a suggestion to find a relation between an exact corrective action and failures and their reasons (Bril et al., 2019).

So, D_{ij} is a value that the risk priority number (RPN) will be divided on, where i characterizes a single corrective action, and j – a new state of a system with its risk numbers. Then the original data for choosing the alternative can be shown in the Table 1.

Table 1. The original data for choosing the alternative

Alternatives of corrective actions	The cost of corrective actions	The future values of RPN (by failure, reason and effect)		
		1	…	n
X	I	D		
1	I_1	D_{11}	…	D_{1n}
…	…	…	…	…
m	I_m	D_{m1}	…	D_{mn}

Let us define the level of single corrective action influence on risk priority number of a single failure as a_{ij}.

$$a_{ij} = 100\% \frac{D_{ij} - I_i}{I_i}$$

We have to make some changes, because the values D_{ij} and I_i in this formula have different dimensions. I_i is measured in Russian rubles and actually does not have any limitations above, but it cannot be less than 0. D_{ij} is the value of a single RPN, so it changes from 1 to 1000 (in the case when the 1 to 10 scale is chosen during evaluation). So, it is necessary to find the relation between the corrective action cost value and risk reduction value (Luo et al., 2015).

Actually it is necessary to answer the question: which amount of money is allowed to invest per risk unit. It is easier to range all costs from 1 to 1000. (Saricam et al., 2015)

However, it is not enough, because D_{ij} is a single risk value, i.e. RPN value and as a result we have the following problem: according to this calculation formula we have the relation of single risk value and corrective action costs (from 1 to 1000), which does not allow to calculate the amount of money spent by the company on risk reduction.

Consequently, D_{ij} has to be shown not by a single risk value, but the level of its reduction. This can be calculated either by the difference of risk priority numbers before or after corrective actions (besides, RPN value after corrective actions is a forecasting one, so it has some uncertainty) or by their relation, that is the calculation of share.

To consider the importance of risk and the level of its reduction we suggest the following procedure. We know both the calculations of RPN before corrective actions implementation and the forecasting risk values after the corrective actions. Let us introduce the risk significance concept and set it equal to the level of original risk according to the scale.

Table 2. RPN values before and after corrective actions

RPN values before corrective actions	**Suggested risk significance scale**	**RPN values after corrective actions**
RPN_{before}	B_p	RPN_{after}
1000	100	700
900	90	600
800	80	500
700	70	400
600	60	100
500	50	100
400	40	100
300	30	100
200	20	100
100	10	100
1	1	1

Let us suggest that original risk is equal to 1000, after corrective actions it will be equal to 700, original risk equal to 900 will turn 600 after corrective actions and so on according to the table.

Then we calculate d_{ij} – the evaluation of risk level change after corrective action implementation as following:

$$d_{ij} = \frac{(RPN_{before} - RPN_{after}) \cdot B_p}{1000},$$

The calculation results are shown in the Table 3.

As a result there can happen a controversial situation, when the risk reduction from 1000 to 700 will be as much significant as a reduction of risk from 600 to 100. This raises some concern, as RPN equal to 1000 is known to have a high probability of heavy injure or even death of staff or user, so its decrease till 700 has to be a priority at any circumstances. Consequently, a risk significance scale cannot be linear.

Table 3. The calculation results

RPN values before corrective actions	**Suggested risk significance scale**	**RPN values after corrective actions**	**Calculation results**
RPN_{before}	B_p	RPN_{after}	d_{ij}
1000	100	700	30
900	90	600	27
800	80	500	24
700	70	400	21
600	60	100	30
500	50	100	20
400	40	100	12
300	30	100	6
200	20	100	2
100	10	100	0
1	1	1	0

If we consider a hyperbolic dependence while calculating a risk significance scale, then the calculation results will be different. The example is shown in the table 4.

Table 4. Risk Significance Calculation results with a hyperbolic dependence

RPN values before corrective actions	**Suggested risk significance scale**	**RPN values after corrective actions**	**Calculation results**
RPN_{before}	B_p	RPN_{after}	d_{ij}
1000	100	700	30
900	72,9	600	21,87
800	51,2	500	15,36
700	34,3	400	10,29
600	21,6	100	10,8
500	12,5	100	5
400	6,4	100	1,92
300	2,7	100	0,54
200	0,8	100	0,08
100	0,1	100	0
1	0,0001	1	0

It is necessary to define the significance of risk, which depends on RPN value before corrective actions, besides the risk significance scale must be nonlinear, the higher is the risk, the higher is the level of its significance.

To consider costs we need to have the information about all failure costs before corrective actions and after them (Gazizulina et al., 2017). This will let us to calculate the effectiveness of corrective actions by costs according to the following formula:

$$K_{eff.} = \frac{C_{before} - C_{after}}{C_{max}},$$

where C_{max} – a maximum value between the costs difference before corrective actions and after them (all planned actions are considered);

C_{before} – Failure costs value of a specific risk;

C_{after} – expected failure costs value after planned corrective actions.

Then by multiplying d_{ij} and $K_{eff.}$ we get a numerical characteristic of corrective actions effectiveness, which considers both an original risk value and the level of its decrease and the amount of money needed for the planned corrective action (Lukichev & Romanovich, 2016). The value range of numerical characteristic of corrective actions effectiveness is (0;100).

Table 5. Values of numerical characteristic of corrective actions effectiveness

Alternatives of corrective actions	Values of numerical characteristic of corrective actions effectiveness		
	1	…	n
X	D		
1	D_{11}	…	D_{1n}
…	…	…	…
m	D_{m1}	…	D_{mn}

Then for a final choice of corrective actions and a plan of their implementation we can use a “minimax regret” principle (Liu et al., 2017).

After mentioned above calculations, we have the following table 6:

Table 6. Values of numerical characteristic with a “minimax regret” principle.

Alternatives of corrective actions	Values of numerical characteristic of corrective actions effectiveness					
	1	*2*	*3*	*4*	*5*	*6*
a	9,33	6,50	2,13	5,84	9,68	7,16
b	6,10	8,80	9,54	4,65	4,10	9,17
c	8,60	7,27	3,91	7,30	9,61	1,63
d	9,96	1,21	0,44	3,90	5,74	4,68
e	2,31	7,79	0,85	1,41	2,67	8,78
f	9,73	4,95	5,92	2,11	1,57	2,85
g	3,84	1,59	7,50	3,46	2,65	9,38
h	1,32	4,47	2,23	2,98	5,92	7,71
i	0,87	4,23	9,61	3,75	1,40	7,40
j	1,25	9,15	4,13	7,07	3,40	3,85
k	7,90	8,21	1,30	3,75	5,32	7,81
maximum	**9,96**	**9,15**	**9,61**	**7,30**	**9,68**	**9,38**

We calculate maximum by each column. The column characterizes the influence of each alternative of corrective action on RPN of each failure.

Then we calculate the maximum as it is shown in the table 7.

Table 7. Modified values of numerical characteristic of corrective actions effectiveness.

Alternatives of corrective actions	Modified values of numerical characteristic of corrective actions effectiveness						**maximum**
a	0,64	2,65	7,48	1,46	0,00	2,21	7,48
b	3,87	0,35	0,07	2,66	5,57	0,21	5,57
c	1,36	1,88	5,70	0,00	0,06	7,75	7,75
d	0,00	7,94	9,17	3,40	3,94	4,70	9,17
e	7,65	1,36	8,76	5,90	7,00	0,60	8,76
f	0,23	4,20	3,69	5,20	8,11	6,53	8,11
g	6,12	7,56	2,11	3,84	7,02	0,00	7,56
h	8,65	4,68	7,38	4,32	3,76	1,66	8,65
i	9,10	4,92	0,00	3,55	8,27	1,98	9,10
j	8,71	0,00	5,48	0,23	6,28	5,53	8,71
k	2,06	0,94	8,31	3,55	4,35	1,56	8,31
						minimum	**5,57**

After that we calculate the minimum in the last column. So, a priority corrective action here is the action “b”.

Then we can develop the plan of corrective action implementation. At first the action “b”, then “a” and so on from the minimum value to maximum.

3. Design Failure Mode and Effect Analysis of a heat-protective coating

To improve the quality and economic efficiency of gas turbine engines, it is necessary to increase the durability of their component parts.

The weakest structural elements of a gas turbine engine, as a rule, are the blades of a gas turbine. The working surfaces of the turbine blades are subjected to intense wear and destruction from exposure to high and variable temperatures. Increasing the service life, reliability and quality of turbine blades is possible due to the application of special protective coatings on the surface of parts by gas-thermal plasma spraying (Chen & Chiang 2015).

To improve the quality of coatings applied by gas-thermal plasma spraying and to prevent the occurrence of risks of coating defects, a Failure Mode and Effects Analysis was applied (FMEA).

The article presents the Design Failure Mode and Effect Analysis of a heat-protective coating applied to the blades of a gas turbine by gas-thermal plasma spraying (DFMEA). A two-layer coating consisting of an outer (ceramic) layer and an inner (metal) sublayer was considered as a plasma heat-protective coating. As a result of the structural analysis, a structural analysis tree of a gas turbine blade with a heat-protective coating Ni-Co-Cr-Al-Y+$ZrO_2/8Y_2O_3$ is constructed, shown in the Figure 1.

The considered structural elements of the structure perform the main functions (picture 2), the failure of which leads to failures: low adhesive strength; low cohesive strength; low heat resistance; low corrosion resistance; low heat resistance; insufficient coating thickness; high roughness of the coating surface.

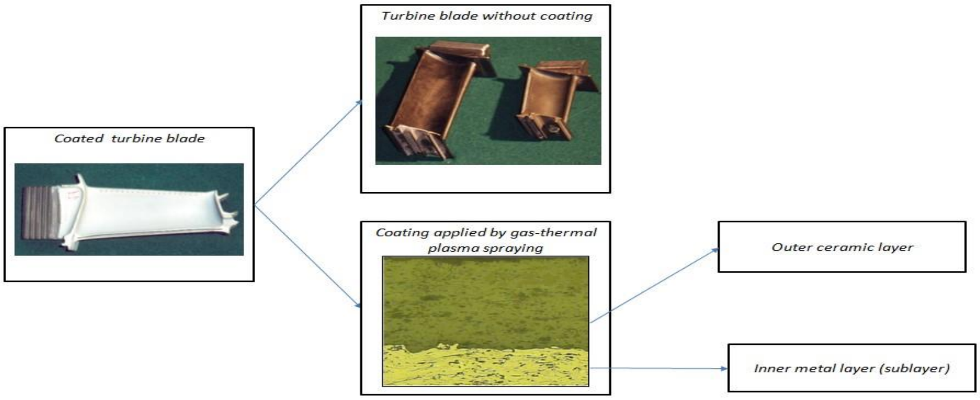

Figure 1. Tree of structural analysis of coated turbine blades

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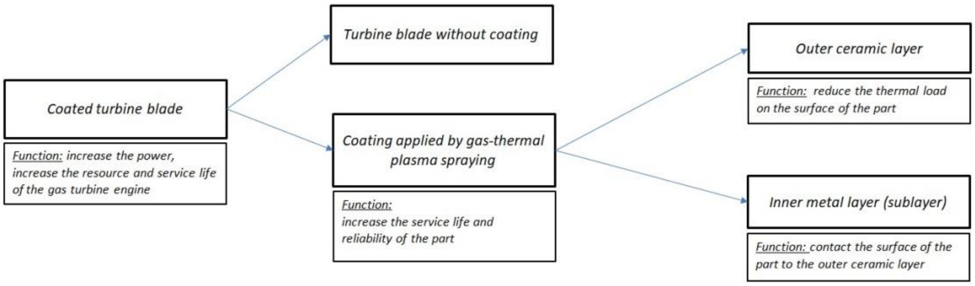


Figure 2. Functional analysis of the coating

Each failure is characterized by a number of reasons for its occurrence, which include: the chemical composition of the powder material, granulation of powder particles, the degree of penetration of particles, the presence of oxides and foreign particles, as well as the structure of the applied coating.

Failures caused by these reasons lead to a loss of operability of coated parts, as well as to a decrease in the service life of the gas turbine engine (figure 3).

The structural analysis, functional analysis and failure analysis carried out made it possible to conduct assessments in accordance with the tables of general criteria of the methodology DFMEA (AIAG & VDA FMEA Handbook-2019 FMEA Handbook: Failure Mode and Effects Analysis (Reference Manual)): significance of the consequences of failure occurrence (S), the possibility of failure occurrence (O) and failure detection measures (D).

Based on the results of the combination of these assessments, the priority of actions to eliminate the risks of failure is set (H(high), M(medium), L(low)). The results of the assessment and the priorities of actions are recorded in the DFMEA protocol chart (figure 4, see Appendix).

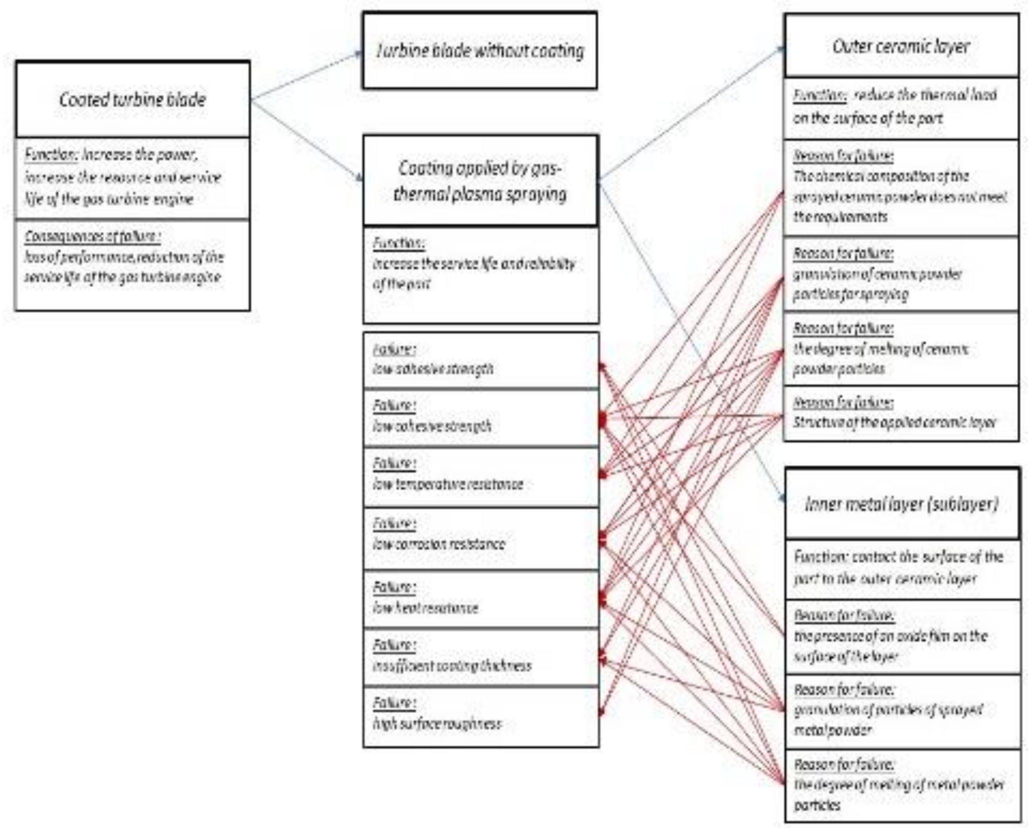


Figure 3. Failure analysis

The Design Failure Mode and Effect Analysis revealed the priorities of actions to eliminate the risks of failures (Chun & Cho, 2015). DFMEA allowed us to develop measures to prevent and detect the causes of failures in the heat-protective coating:

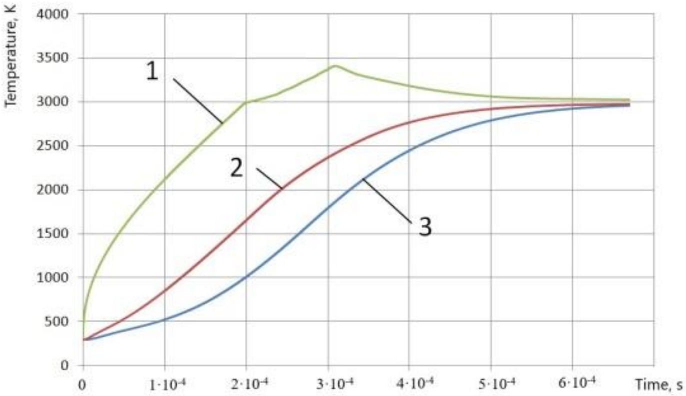
- investigation of the effect of the granulometric composition of the powder on the quality of the coating;
- simulation of heating and melting of the sprayed powder material in a plasma jet;
- investigation of the strength properties of the coating of a layered structure that allows us to develop a coating method for obtaining the necessary structure of a heat-protective coating.

To improve the quality of the design of the heat-protective coating applied to the blades of a gas turbine, the implementation of the developed measures was carried out. Since the powder material to be sprayed, depending on the specific supplier, has a different shape and a large spread of particles in diameters, therefore, the powder particles, moving in the plasma jet, accelerate to different speeds, and also have different trajectories of movement; they are in the high-temperature part of the plasma jet for different times; and under the influence of convective heat exchange and radiation heat exchange, they are heated to different temperatures.

As a result, the particles of the powder material during the formation of the coating have different degrees of melting and deformation. The study of the influence of the granulometric composition of the powder was carried out on the basis of the study of the movement of particles in a plasma jet by the method of high-speed video shooting.

The particle velocity was measured in cross sections at a distance of 60 and 80 mm from the nozzle section. Studies have shown that the velocities of particles during their flight in the plasma flow vary in cross-section and range from 90 to 150 m/s, which prove the presence of separation of particles of powder material in the plasma jet.

Studies of heating and melting of the sprayed powder material in a plasma jet were carried out using the ANSYS software. As a result of the simulation, the dependences of the temperature of the sprayed particle on the time of its stay in the plasma flow are obtained (Figure 5).



1 – the surface of the particle;
2 - the layer of the particle located between the surface and its center;
3 – the core of the particle

Figure 5. The dependence of the temperature of a particle with a diameter of 60 microns on the time of its stay in the plasma stream

The analysis of the obtained dependences allowed us to establish the volume degree of melting of the particles, which cannot be determined by numerical methods. It is established that particles with a diameter of up to 10 microns completely reach the evaporation temperature, from 10 to 20 microns completely melt; from 20 to 60 microns melt to a depth of 40 to 60%, while their core remains in the solid phase, and particles with a diameter of more than 80 microns melt to a depth of only 20 to 27%, remaining mostly non-molten solid particles.

Based on the results obtained, using the ANSYS software product, a coating applied with a powder material was modeled, taking into account the presence of two phases after spraying: the inner-solid, not molten, and the outer-crystallized, molten (Figure 6).

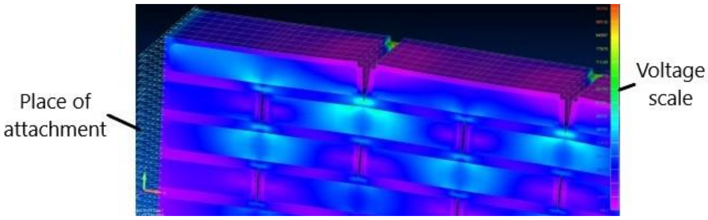


Figure 6. Model of the stress-strain state of a coating applied with a powder of 60 microns

To estimate the stresses depending on the particle size, the parameter k is introduced, which is equal to the ratio of the particle diameter to its height:

$$k = \frac{D_k}{h_k}$$

Modeling of the loading of the coated sample allowed us to obtain the dependence of the maximum stresses in the sample on the parameter *k* (Figure 7). The analysis of the dependence showed that the coating with the parameter *k* in the range from 4.3 to 5.3 resists the load in the best way (Cheng et al., 2015).

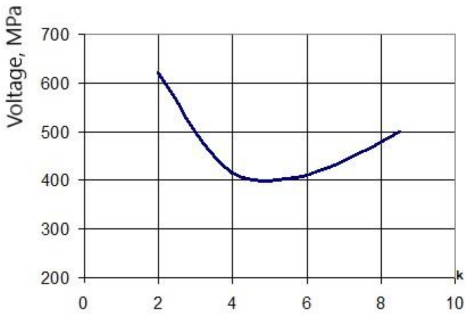


Figure 7. Dependence of the maximum stresses in the sample on the parameter *k*

4. Conclusion

As a result of our research, FMEA under uncertainty appears to be a controlled procedure. The results show mainly risks, which allows us to arrange corrective actions effectively.

To ensure a given degree of order of the coating in the formed layer, it is necessary to introduce an additional operation for sieving the powder material in the coating process to isolate a narrow fraction of powder particles.

Also, determine the technological parameters of the coating process necessary for the coating of the required structure corresponding to the maximum strength.

As a result of the study of the influence of the granulometric composition of the powder on the quality of the coating, the study of heating and melting of the sprayed powder material in a plasma jet and the study of the strength properties of the coating of the layered structure, the method of coating is described.

The developed method makes it possible to obtain heat-protective coatings that have a high damping ability, resistance to alternating mechanical and temperature stresses, as well as the ability to localize fatigue damage and microcracks inside the crystallite grain, without allowing cracks to grow to the structural material of the part base.

The implementation of the measures established during the DFMEA allowed to improve the quality of the heat-protective coating applied to the blades of the gas turbine. The re-evaluation allowed us to obtain reduced values of the significance of the consequences of failure occurrence (S), the possibility of failure occurrence (O) and failure detection measures (D), therefore, the priorities of actions to eliminate the risks of failure have changed from high (H) for medium (M) and low (L) (picture 4).

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Appendix

Failure Analysis (Stage 4)				Risk analysis (Stage 5)						Optimization (Stage 6)					
1. The consequence of the failure of the top level element	[illegible]	1.Failure of the element in question	1. The reason for the failure of the next lower level element or characteristic	Current warning actions	[illegible]	Current detection actions	[illegible]	[illegible]	[illegible]	Prevention actions	Detection actions	[illegible]	[illegible]	[illegible]	[illegible]
loss of performance,reduction of the service life of the gas turbine engine	8	low adhesive strength	2. the presence of an oxide film on the surface of the layer	Use for spraying powder with a chemical composition that meets the design requirements	1	Conducting input control of the powder material	3	L		-	-				
			2. the degree of melting of metal powder particles	-	10	The metallographic control of the coating structure has been introduced into the technical process of coating application	6	H		Simulation of heating and melting of the sprayed powder material in a plasma jet	-	8	3	6	M
			2. granulation of particles of sprayed metal powder	Selection of the required granulation powder from the supplier	7	Conducting input control of the powder material	4	H		Investigation of the effect of the granulometric composition of the powder on the quality of the coating	A preparatory operation was introduced into the technical process of coating application - powder seeding	8	3	2	L
loss of performance,reduction of the service life of the gas turbine engine	8	low cohesive strength	1. The chemical composition of the sprayed ceramic powder does not meet the requirements	Use for spraying powder with a chemical composition that meets the design requirements	1	Conducting input control of the powder material	3	L		-	-				
			1. granulation of ceramic powder particles for spraying	Selection of the required granulation powder from the supplier	7	Conducting input control of the powder material	4	H		Investigation of the effect of the granulometric composition of the powder on the quality of the coating	A preparatory operation was introduced into the technical process of coating application - powder seeding	8	3	2	L
			1. the degree of melting of ceramic powder particles	-	10	The metallographic control of the coating structure has been introduced into the technical process of coating application	6	H		Simulation of heating and melting of the sprayed powder material in a plasma jet	-	8	3	6	M
			1. Structure of the applied ceramic layer	-	10	The metallographic control of the coating structure has been introduced into the technical process of coating application	6	H		Development of a coating method for obtaining a layered structure	-	8	1	6	L
			2. the presence of an oxide film on the surface of the layer	Use for spraying powder with a chemical composition that meets the design requirements	1	Conducting input control of the powder material	3	L		-	-				
			2. granulation of particles of sprayed metal powder	Selection of the required granulation powder from the supplier	7	Conducting input control of the powder material	4	H		Investigation of the effect of the granulometric composition of the powder on the quality of the coating	A preparatory operation was introduced into the technical process of coating application - powder seeding	8	3	2	L
			2. the degree of melting of metal powder particles	-	10	The metallographic control of the coating structure has been introduced into the technical process of coating application	6	H		Simulation of heating and melting of the sprayed powder material in a plasma jet	-	8	3	6	M
loss of performance,reduction of the service life of the gas turbine engine	8	low temperature resistance	1. The chemical composition of the sprayed ceramic powder does not meet the requirements	Use for spraying powder with a chemical composition that meets the design requirements	1	Conducting input control of the powder material	3	L		-	-				
			1. granulation of ceramic powder particles for spraying	Selection of the required granulation powder from the supplier	7	Conducting input control of the powder material	4	H		Investigation of the effect of the granulometric composition of the powder on the quality of the coating	A preparatory operation was introduced into the technical process of coating application - sieve powder seeding	8	3	2	L
			1. the degree of melting of ceramic powder particles	-	10	The metallographic control of the coating structure has been introduced into the technical process of coating application	6	H		Simulation of heating and melting of the sprayed powder material in a plasma jet	-	8	3	6	M
			1. Structure of the applied ceramic layer	-	10	The metallographic control of the coating structure has been introduced into the technical process of coating application	6	H		Development of a coating method for obtaining a layered structure	-	8	1	6	L
loss of performance,reduction of the service life of the gas turbine engine	8	low corrosion resistance	1. granulation of ceramic powder particles for spraying	Selection of the required granulation powder from the supplier	7	Conducting input control of the powder material	4	H		Investigation of the effect of the granulometric composition of the powder on the quality of the coating	A preparatory operation was introduced into the technical process of coating application - powder seeding	8	3	2	L
			1. the degree of melting of ceramic powder particles	-	10	The metallographic control of the coating structure has been introduced into the technical process of coating application	6	H		Simulation of heating and melting of the sprayed powder material in a plasma jet	-	8	3	6	M
			1. Structure of the applied ceramic layer	-	10	The metallographic control of the coating structure has been introduced into the technical process of coating application	6	H		Development of a coating method for obtaining a layered structure	-	8	1	6	L
			2. granulation of particles of sprayed metal powder	Selection of the required granulation powder from the supplier	7	Conducting input control of the powder material	4	H		Investigation of the effect of the granulometric composition of the powder on the quality of the coating	A preparatory operation was introduced into the technical process of coating application - powder seeding	8	3	2	L
			2. the degree of melting of metal powder particles	-	10	The metallographic control of the coating structure has been introduced into the technical process of coating application	6	H		Simulation of heating and melting of the sprayed powder material in a plasma jet	-	8	3	6	M

Figure 4. Fragment of the DFMEA chart