Modeling of mechanical characteristics of composite materials applied for protection of information and control complexes of aircraft

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Abstract. In modern conditions of electronic warfare, effective protection of information and control complexes of aircraft (AC) from the destructive effects of external interference is impossible without the use of innovative solutions in the field of creating new composite materials (CM) with radio-absorbing properties. This scientific area is inextricably linked with the issues of predicting the properties of these materials. A wide variety of design solutions to protect aircraft “electronics”, as well as a wide range of electromagnetic and mechanical effects, require the creation of functional materials for specific operating conditions. Thus, the developers of functional materials must have an effective tool to predict the properties of the CM being created. Solutions can be based on mathematical models that allow predicting the properties of CM and subsequently optimizing their composition. The article discusses the identification and verification of mathematical models of the mechanical characteristics of CMs based on BASF polyurethane with the addition of both untreated and processed ferric iron oxide as a filler, with subsequent optimization of the characteristics and determination of the corresponding CM composition with radio-absorbing properties. Experimental studies have been carried out, which confirm the adequacy of the developed mathematical models.

1. Introduction

In modern realities, the aerospace industry is one of the main customers and consumers of composite materials (CM) with radio-absorbing properties. Due to the use of these materials in the designs of aircraft (AC), the effect of electromagnetic radiation on the information and control systems of aircraft is reduced. Modern aircraft, as a rule, operate in an aggressive environment, which necessitates continuous improvement of design solutions to protect aircraft “electronics”. The problem of improving the quality of protection against electromagnetic radiation of electronic units of aircraft information and control complexes is inextricably linked with the level of materials used, which is determined by their functional properties. Such materials can be various CMs with given physical and mechanical characteristics.

In the context of the active introduction of new CMs in the design of aircraft for protection from electromagnetic radiation, domestic and foreign enterprises of the chemical industry are engaged in the creation and production of CMs with radio-absorbing properties. These materials are obtained as a result of the chemical interaction of a polymer binder, filler and modifier. Moreover, the percentage of filler (for example, ferric oxide) determines the reflection coefficient of electromagnetic radiation, thereby improving its physical parameters. However, such fillers,
as a rule, have a negative effect on the mechanical characteristics of CM, which may not have the best effect on the possibility of manufacturing structural elements for the protection of aircraft information and control systems. To reduce the time for creating new CMs, specialists need mathematical models that allow describing the relationship between the characteristics of materials depending on their composition, which can then be used in the decision support system on the CM composition [1–3]. It should be noted that the reflection coefficient of electromagnetic radiation, determined by the percentage of filler content, is the main property that determines the possibility of using the created material to protect control units from electromagnetic radiation. Therefore, in the process of multi-criteria optimization of the physical and mechanical characteristics of CM, a change in the reflection coefficient of electromagnetic waves is unacceptable. In this regard, in the future, we will consider the mathematical models of the mechanical characteristics of CM, allowing in the process of multi-criteria optimization to change the characteristics by a certain amount of concession.

2. Requirements for mathematical models of mechanical characteristics of composite materials

In the general case, the model of mechanical characteristics of CM can be quantitatively characterized using input (mechanical effects on structural elements made using CM), internal (CM components) and output (mechanical characteristics of CM) parameters.

In the mathematical modeling of the mechanical characteristics of CM, the values of the output parameters (mechanical characteristics of CM) and the ranges of their possible change are determined in accordance with the technical specifications for the development of CM, the input parameters characterize the operating conditions where structural elements made of CM are used, i.e. mechanical impact level.

To identify mathematical models of mechanical characteristics, it is proposed to use a special cubic multiple regression function [4, 5].

The vector of coefficients of the mathematical model is determined using the least squares method in matrix form by the formula

$$B = (F^T F)^{-1} F^T Y,$$

where $B$ is the vector of the desired coefficients, $Y$ is the column of experimental values of the dependent variable, $F$ is the matrix of the experimental design.

The use of QFD analysis made it possible to determine and rank, in order of decreasing significance, the mechanical characteristics of CM: Shore hardness, tensile strength, tensile elongation.

3. Identification and verification of mathematical models of mechanical characteristics of composite materials

We will consider the process of identification and verification of the mathematical model of the mechanical characteristics of CM with radio-absorbing properties using the example of CM with a polymer binder—polyurethane BASF. It should be noted that the treatment of the filler with dichloromethyl phosphate affects the fire retardant properties and elasticity properties. This should be taken into account when developing mathematical models: for experimental studies, samples with different compositions and with processed and unprocessed fillers were made.

3.1. Development of mathematical models for a group of samples without filler processing

BASF polyurethane was used as a polymer binder (component $x_1$). The percentage of polymer together with the hardener (component $x_3$) ranges from 30 to 70%. The hardener is one fifth of the mass content of the polymer binder. Trivalent iron oxide (without mechanochemical treatment) with a percentage of 30 to 70% was taken as a filler (component $x_2$).
Table 1. Results of hardness measurements for a group of samples without filler treatment.

| Sample No. | Content of polymer binder with hardener, wt. % | Filler content, wt. % | Filler processing | Hardness, conventional units | Average value, conventional units |
|------------|-----------------------------------------------|-----------------------|------------------|-----------------------------|---------------------------------|
| RA.15      | 70                                            | 30                    | No               | 42                          | 35                              | 41                              | 41                              | 40                              | 39.8                            |
| RA.16      | 60                                            | 40                    | No               | 40                          | 49                              | 42                              | 44                              | 44                             | 44.6                            |
| RA.17      | 50                                            | 50                    | No               | 51                          | 45                              | 46                              | 44                              | 44                             | 45.6                            |
| RA.18      | 45                                            | 55                    | No               | 46                          | 42                              | 47                              | 50                              | 45                             | 46.0                            |
| RA.19      | 40                                            | 60                    | No               | 52                          | 55                              | 52                              | 53                              | 53                             | 53.6                            |
| RA.20      | 35                                            | 65                    | No               | 55                          | 52                              | 58                              | 54                              | 50                             | 53.8                            |
| RA.21      | 30                                            | 70                    | No               | 85                          | 70                              | 75                              | 80                              | 76                             | 77.2                            |

The results of measuring the hardness of samples of this group are presented in table 1. The mathematical model for hardness ($\tilde{y}_{\text{hard1}}$) has the form:

$$\tilde{y}_{\text{hard1}} = 54.3x_1 + 239x_2 - 703.6x_3 - 320.3x_1x_2 + 1148.4x_1x_3.$$  

The results of measuring the tensile strength and elongation at break of the samples are presented in table 2.

Table 2. Average values of tensile strength and elongation at break for a group of samples without filler treatment.

| Sample No. | Content of polymer binder with hardener, wt. % | Filler content, wt. % | Filler processing | Tensile strength, MPa | Elongation at break, % |
|------------|-----------------------------------------------|-----------------------|------------------|-----------------------|------------------------|
| RA.15      | 70                                            | 30                    | No               | 0.273                 | 38                     |
| RA.16      | 60                                            | 40                    | No               | 0.143                 | 10                     |
| RA.17      | 50                                            | 50                    | No               | 0.835                 | 16                     |
| RA.18      | 45                                            | 55                    | No               | 0.722                 | 31                     |
| RA.19      | 40                                            | 60                    | No               | 0.634                 | 15                     |
| RA.20      | 35                                            | 65                    | No               | 0.298                 | 32                     |
| RA.21      | 30                                            | 70                    | No               | 0.230                 | 40                     |

The mathematical model for ultimate tensile strength ($\tilde{y}_{\text{strength1}}$) has the form:

$$\tilde{y}_{\text{strength1}} = -6.087x_1 - 3.932x_2 + 11.305x_3 + 20.117x_1x_2 - 1.289x_1x_3.$$  

The mathematical model for elongation at break ($\tilde{y}_{\text{el1}}$) has the form:

$$\tilde{y}_{\text{el1}} = -156x_1 + 276x_2 + 1343x_3 - 381x_1x_2 - 3760x_1x_3.$$  

3.2. Development of mathematical models for a group of samples with filler processing

BASF polyurethane was used as a polymer binder (component $x_1$). The percentage of polymer together with the hardener (component $x_3$) ranges from 30 to 70%. The hardener is one fifth
of the mass content of the polymer binder. Trivalent iron oxide (treated with phosphoric acid derivatives) with a percentage of 30 to 70% was taken as a filler (component $x_2$).

The results of measuring the hardness of samples of this group are presented in table 3.

**Table 3.** Results of hardness measurements for a group of samples with filler treatment.

| Sample No. | Content of polymer binder with hardener, wt. % | Filler content, wt. % | Filler processing | Hardness, conventional units | Average value, conventional units |
|------------|-----------------------------------------------|-----------------------|------------------|-----------------------------|----------------------------------|
| RA.22      | 70                                            | 30                    | Yes              | 38                          | 37                               |
| RA.23      | 60                                            | 40                    | Yes              | 42                          | 44                               |
| RA.24      | 50                                            | 50                    | Yes              | 41                          | 45                               |
| RA.25      | 45                                            | 55                    | Yes              | 48                          | 47                               |
| RA.26      | 40                                            | 60                    | Yes              | 54                          | 50                               |
| RA.27      | 35                                            | 65                    | Yes              | 53                          | 56                               |
| RA.28      | 30                                            | 70                    | Yes              | 62                          | 61                               |

The mathematical model for hardness ($\tilde{y}_{\text{hard2}}$) has the form:

$$\tilde{y}_{\text{hard2}} = 88.5x_1 + 117.2x_2 - 85.7x_3 - 196.5x_1x_2 - 31.9x_1x_3.$$  

The results of measuring the tensile strength and elongation at break of the samples are presented in table 4 (the average values for the tests of five samples are indicated).

**Table 4.** Average values of tensile strength and elongation at break for a group of samples with filler treatment.

| Sample No. | Content of polymer binder with hardener, wt. % | Filler content, wt. % | Filler processing | Tensile strength, MPa | Elongation at break, % |
|------------|-----------------------------------------------|-----------------------|------------------|------------------------|------------------------|
| RA.22      | 70                                            | 30                    | Yes              | 0.077                  | 60                     |
| RA.23      | 60                                            | 40                    | Yes              | 0.142                  | 16                     |
| RA.24      | 50                                            | 50                    | Yes              | 0.828                  | 61                     |
| RA.25      | 45                                            | 55                    | Yes              | 1.123                  | 52                     |
| RA.26      | 40                                            | 60                    | Yes              | 0.211                  | 48                     |
| RA.27      | 35                                            | 65                    | Yes              | 0.656                  | 44                     |
| RA.28      | 30                                            | 70                    | Yes              | 0.015                  | 9                      |

The mathematical model for ultimate tensile strength ($\tilde{y}_{\text{strength2}}$) has the form:

$$\tilde{y}_{\text{strength2}} = -1.57x_1 - 5x_2 + 24.6x_3 + 17.04x_1x_2 - 48.15x_1x_3.$$  

The mathematical model for the elongation at break ($\tilde{y}_{el2}$) has the form:

$$\tilde{y}_{el2} = -308.6x_1 - 179.5x_2 + 719.3x_3 + 792.7x_1x_2 + 673.6x_1x_3.$$
4. Optimization of the mechanical properties of composite materials

Multi-criteria optimization of mechanical characteristics of CM was carried out using special software (Certificate of state registration of a computer program No. 2020616892), which implements the method of successive concessions with a risk assessment according to the Savage criterion [6, 7].

Optimization of mechanical characteristics of a group of samples without filler treatment. The maximum value of Shore hardness is 77.24 conventional units with the following percentage ratio of the components: $x_1 - 24\%; x_2 - 66\%; x_3 - 10\%$.

After finding the maximum value of the first criterion in importance (Shore hardness) in the region of admissible solutions, the maximum value of the next most important criterion (tensile strength) is found. However, in this case, the following condition must be met—the value of the first criterion should not deviate from its maximum value by more than the amount of the permissible concession (in this case, $\delta_1 = 12$). Thus, the problem is solved: $Z_2(\bar{X}) \rightarrow \max, Z_1(\bar{X}) \geq 65.24$. When solving it, the maximum value of the ultimate strength is $98 \cdot 10^6$ Pa at the following percentage ratio of the components: $x_1 - 37\%; x_2 - 49\%; x_3 - 14\%$.

At the next stage of optimization, the value of the concession $\delta_2$ is used according to the second criterion, which, together with the first concession, is applied when finding the conditional maximum of the third particular criterion (relative elongation in tension): $Z_3(\bar{X}) \rightarrow \max, Z_1(\bar{X}) \geq 27.99, Z_2 \geq 0.78 \cdot 10^6$.

The maximum tensile elongation is 38.20% with the following percentage of components: $x_1 - 56\%; x_2 - 30\%; x_3 - 14\%$.

Thus, to obtain a new CM with a hardness value of 39.83 conventional units, a tensile strength of $0.27 \cdot 10^6$ Pa, a tensile elongation of 38.20%, the following composition of components is required: polyurethane BASF (matrix)—56%; iron oxide (powder filler)—30%; hardener—14%.

Optimization of mechanical characteristics of a group of samples with filler treatment. The maximum Shore hardness value is 58.13 conventional units with the following percentage ratio of the components: $x_1 - 24\%; x_2 - 66\%; x_3 - 10\%$.

After finding the maximum value of the first criterion in importance (Shore hardness) in the region of admissible solutions, the maximum value of the next most important criterion (tensile strength) is found. However, in this case, the following condition must be met—the value of the first criterion should not deviate from its maximum value by more than the amount of the permissible concession (in this case, $\delta_1 = 12$). Thus, the problem is solved: $Z_2(\bar{X}) \rightarrow \max, Z_1(\bar{X}) \geq 65.24$. When solving it, the maximum value of the ultimate strength is $98 \cdot 10^6$ Pa at the following percentage ratio of the components: $x_1 - 37\%; x_2 - 49\%; x_3 - 14\%$.

At the next stage of optimization, the value of the concession $\delta_2$ is used according to the second criterion, which, together with the first concession, is applied when finding the conditional maximum of the third particular criterion: $Z_3(\bar{X}) \rightarrow \max, Z_1(\bar{X}) \geq 31.28, Z_2 \geq 0.83 \cdot 10^6$.

The maximum tensile elongation is 42.65% with the following percentage of components: $x_1 - 56\%; x_2 - 30\%; x_3 - 14\%$.

Thus, to obtain a new RA DFPCM with a hardness value of 42.20 conventional units, a tensile strength of $0.27 \cdot 10^6$ Pa, a tensile elongation of 42.65%, the following composition of components is required: polyurethane BASF (matrix)—56%; iron oxide (powder filler)—30%; hardener—14%.

5. Determination of the accuracy of predicting the mechanical characteristics of composite materials

In the previous paragraph, using mathematical modeling, CM compositions were obtained with optimal values of mechanical characteristics (Shore hardness, tensile strength, tensile elongation). To determine the error in predicting the mechanical characteristics of CM, experimental studies were carried out by comparing the results of measurements of Shore hardness, tensile strength, and tensile elongation with the results of mathematical modeling. The maximum Shore hardness value is 58.13 conventional units with the following percentage ratio of the components: $x_1 - 24\%; x_2 - 66\%; x_3 - 10\%$.

Thus, to obtain a new CM with a hardness value of 39.83 conventional units, a tensile strength of $0.27 \cdot 10^6$ Pa, a tensile elongation of 38.20%, the following composition of components is required: polyurethane BASF (matrix)—56%; iron oxide (powder filler)—30%; hardener—14%.
Table 5. Comparison of measurement results and calculated optimal values for a group of samples with treated filler.

| Feature name and unit                  | Calculated optimal values | Measurement results | Arithmetic mean | Standard deviation | Confidence limits |
|----------------------------------------|---------------------------|---------------------|-----------------|-------------------|------------------|
| Shore hardness, conventional units     | 39.83                     | 38                  | 41              | 40                | 38               |
|                                        |                           |                     | 40              | 42                | 42               |
|                                        |                           |                     | 0.270           | 0.280             | 0.270            |
|                                        |                           |                     | 0.272           | 0.275             | 0.278            |
| Tensile strength, MPa                 | 0.270                     | 0.273               | 0.003           | 0.007             |                  |
|                                        |                           |                     | 0.265           | 0.272             |                  |
|                                        |                           |                     | 0.278           | 39                |                  |
|                                        |                           |                     | 36              | 35                |                  |
|                                        |                           |                     | 38              | 42                |                  |
| Tensile elongation, %                  | 38.20                     | 38                  | 1.225           | 3.399             |                  |
|                                        |                           | 36                  | 35              | 38                | 42               |

Table 6. Comparison of measurement results and calculated optimal values for a group of samples without treated filler.

| Feature name and unit                  | Calculated optimal values | Measurement results | Arithmetic mean | Standard deviation | Confidence limits |
|----------------------------------------|---------------------------|---------------------|-----------------|-------------------|------------------|
| Shore hardness, conventional units     | 42.20                     | 41                  | 45              | 43                | 40               |
|                                        |                           |                     | 40              | 44                | 44               |
|                                        |                           |                     | 1.05            | 1.13              | 1.04             |
|                                        |                           |                     | 1.06            | 1.02              | 1.04             |
| Tensile strength, MPa                 | 1.03                      | 1.06                | 0.019           | 0.052             |                  |
|                                        |                           |                     | 1.04            | 1.06              | 1.02             |
|                                        |                           |                     | 43              | 41                | 40               |
|                                        |                           |                     | 41              | 42                | 42               |
| Tensile elongation, %                  | 42.65                     | 41                  | 0.707           | 1.963             |                  |
|                                        |                           | 40                  | 41              | 39                |                  |

hardness, tensile strength, tensile elongation with values calculated using mathematical models. For this, five samples of CM were made, the composition of which was optimized using verified mathematical models. The measurement results for each group of samples (with and without filler treatment) are shown in tables 5 and 6, respectively.
Analysis of the results of experimental studies allows us to conclude that:

1. The relative error of mathematical models for hardness, tensile strength and tensile elongation for samples consisting of polyurethane BASF (polymer binder), untreated ferric iron oxide and hardener is 2.38, 1.1 and 0.52%, respectively.

2. The relative error of mathematical models for hardness, tensile strength and tensile elongation for samples consisting of polyurethane BASF (polymer binder), treated with dichloromethyl phosphate filler and hardener is 0.94, 2.83 and 3.87%, respectively.

6. Conclusion

In accordance with the proposed process of modeling the mechanical characteristics of CM, it is necessary to develop mathematical models based on processing the results of measurements of the CM output parameters. For this, it is necessary to conduct experimental studies related to the measurement of the output parameters (mechanical characteristics of materials) of CM, and in the subsequent generalization of the results of these measurements in algorithmic form or in the form of analytical dependencies. In this case, special attention should be paid to the process of identifying the mathematical model of CM, the correct solution of which determines the accuracy of modeling the mechanical characteristics of CM and their subsequent optimization.

As a result of the experimental studies, the error in modeling the optimized CM characteristics was determined, which does not exceed 4%, which proves the possibility of using the developed mathematical models when creating new CMs, taking into account their mechanical properties.

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