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QUALITY MANAGEMENT OF DISPERSION-STRENGTHENED ALUMINUM-BASED SAP-ISML COMPOSITE ALLOY

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Abstract

The article is devoted to the analysis of the composition and properties of dispersion-strengthened aluminum-based SAP-ISML composite materials, which are used in various industries, including the aviation. The properties of such materials have been analyzed with the aim of ensuring the management of their quality for rational use and subsequent disposal. Mathematical models of dependence of parameters of dispersed-hardened materials on the basis of aluminum of SAP-ISML type on the aluminum content and temperature are constructed.

Keywords: composite material, dispersion-strengthened, aluminum, SAP-ISML, mathematical model, yield strength, ultimate strength, experimental design

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1. Introduction

Nowadays, composite materials (CM) are often used in engineering. The use of these materials is aimed at obtaining such products, which will be resistant to loads of various types and, simultaneously, to reduce the total weight of the resulting product. Therefore, they are used for such industries as automotive, aircraft and space technology, building industry, etc. At the moment, there are 2 types of composite materials used for these purposes:

1) CMs based on a metal matrix;

2) CMs based on a nonmetallic matrix.

The most used CMs with a nonmetallic matrix are polymeric carbon fibers, boron fibers and organofibers [1]. They are the materials for various parts of aviation equipment – chassis, bearings, disks of aircraft brakes, and so on.

As for CMs with a metal matrix, they are made on the basis of various metals: aluminum, beryllium, magnesium, nickel, cobalt, chromium, etc. Such materials are called dispersion-strengthened composite materials (DSCM) [2]. DSCM belong to the group of composite materials, which are made, mainly, by methods of powder metallurgy. The microstructure of DSCMs consists of polycrystalline matrices in which the particles (mainly oxides, carbides and/or nitrides) are dispersed [3]. Their peculiarity is that the matrix of metal or alloy is strengthened by fine-dispersed artificially introduced particles having a size of 0.1 to 15 μm in an amount from 0.1 to 15 %. As a strengthening phase, dispersed oxide particles, carbides, nitrides and other refractory compounds are used.

After formation and sintering, a hot plastic deformation is carried out to produce a composite material, resulting in a dense semi-finished product without pores (tape, strip, profile).

This research is devoted to aluminum-based DSCMs of SAP-ISML type. Such materials are used, for example, for cladding gondolas of power plants in the exhaust zone, piston rods, compressor blades and other elements that are not exposed to high temperatures

As it is noted in [4], oxides are used most widely as compounds used as a strengthening phase in aluminum-based DSCMs and its alloys. At the moment there are 3 domestic brands of aluminum-based DSCMs: САП-1, САП-2 and САП-3. The difference of these materials differs from each other in the difference in the concentration of oxides (from 6 % to 9 % of Al_2O_3 for САП-1, from 9 % to 13 % of Al_2O_3 for САП-2, from 13 % to 17 % of Al_2O_3 for САП-3) [4]. Also, they contain up to 25 % silicon and up to 5 % iron. In addition to these materials, there are also Al-C DSCMs. In such materials the role of the strengthening phase is performed by Al_4C_3 aluminum carbide [5].

The foreign counterparts of the above DSCMs are, respectively, for САП-1 – SAP-930, for САП-2 – SAP-895, for САП-3 – SAP-865. They are distinguished by increased structural stability and corrosion resistance due to the reduced iron content in the matrix (less than 0.1 %), which somewhat differs their properties from the properties of SAP-type materials [5].

Studies show that with an increase in Al_2O_3 content in materials of this type, an increase in the hardness and strength parameters is observed, in contrast to the thermal and electrical conductivity, the coefficient of thermal expansion and plasticity, which decrease [6–10].

Studies have shown that at temperatures of 300–500 °C, aluminum-based DSCMs is superior in strength to all industrial aluminum alloys and is characterized by high strength and creep characteristics [4].

Until this time, the task of determining the parameters of aluminum-based DSCMs and modeling their properties for quality management in the process of creation, operation and disposal has not been fully reflected in the studies. In particular, the properties of the SAP type alloys are investigated in [11], while alloys of the SAP-ISML type are not fully investigated. The study of the parameters of aluminum-based DSCMs will make it possible to single out their main significant parameters, to assess the starting point from which values of the studied parameters will have a significant impact on the requirements imposed on them. This will optimize the composition of these materials in terms of both operation and subsequent disposal.

The aim of research is to analyze the properties and composition of dispersion-strengthened aluminum-based SAP-ISML composite materials used for aerospace engineering and other industries, as well as to select their optimal parameters to ensure the determination of the quality parameters applied to them.

To achieve this aim, the following tasks are solved:

– development of a mathematical model for determination of relationship of the chemical composition and properties of the aluminum-based DSCMs, such as SAP-ISML;

– analysis and identification of the possibility of clarifying the requirements for the composition and properties of the aluminum-based DSCMs, to ensure the management of their quality.

2. Materials and methods of research

Table 1 of the experimental material is taken on the basis of [4].

Table 1

Mechanical properties of aluminum-based DSCMs of the SAP-ISML type

Material	t, °C	YS, MPa	US, MPa
SAP-ISML-930	20	175	250
	300	95	110
	400	75	85
	500	65	70
SAP-ISML-895	20	215	310
	300	120	150
	400	100	110
	500	85	90
SAP-ISML-865	20	265	380
	300	155	175
	400	120	130
	500	85	105

Note: t – the test temperature of the sample; YS – yield strength; US – ultimate strength

The analysis of the obtained data allows to use the plan of the full factorial experiment and determine the values of the output and input variables, taking into account the fact that the number of experiments corresponds to $N=2^k$. The model is obtained on the basis of the method of constructing of the second order complete central orthogonal central design, the principles of its use for analogous problems are described in [12, 13]. The values of the input variables are normalized according to the following formulas:

$$x_1 = \frac{x_1^* - \overline{x}_1}{I_1}, \quad (1)$$

$$x_2 = \frac{x_2^* - \overline{x}_2}{I_2}, \quad (2)$$

where x_1 and x_2 – the normalized values of the input variables, x_1^*, x_2^*, – the natural values of the input variables, $\overline{x}_1$, $\overline{x}_2$ – the average values of the input variables $\overline{x}_1$=11 %, $\overline{x}_2$=260, I_1, I_2 – the variation intervals of the input variables (I_1=4, I_2=240).

The mathematical model is described by a polynomial of the following form:

$$Y_i = a_0 + a_1x_1 + a_2x_2 + a_3(x_1^2 - \beta) + a_4(x_2^2 - \beta) + a_5x_1x_2, \quad (3)$$

where a_i – the estimated coefficients, β – the parameter that is calculated depending on the number of kernel points of the composite plan 2^{n-p} of the shoulder of the "star" points α and the number of plan points according to the formula:

$$\beta = \frac{\sum_{j=1}^{N}(x_i^j)^2}{N} = \frac{2^{n-p} + \alpha}{N}. \quad (4)$$

A general view of the data for construction of a central orthogonal composite design is given in **Table 2**.

Table 2

Presentation of data for construction of a central orthogonal composite design

№ of experiment	x_1	x_2	$x_1^2 - \beta$	$x_2^2 - \beta$	Y_{ij}
1	x_1^{max}	x_2^{max}	$x_1^{max} - 0,6667$	$x_2^{max} - 0,6667$	Y_{i1}
2	x_1^{min}	x_2^{max}	$x_1^{min} - 0,6667$	$x_2^{max} - 0,6667$	Y_{i2}
3	x_1^{max}	x_2^{min}	$x_1^{max} - 0,6667$	$x_2^{min} - 0,6667$	Y_{i3}
4	x_1^{min}	x_2^{min}	$x_1^{min} - 0,6667$	$x_2^{min} - 0,6667$	Y_{i4}
5	x_1^{max}	x_2^{av}	$x_1^{max} - 0,6667$	$x_2^{av} - 0,6667$	Y_{i5}
6	x_1^{min}	x_2^{av}	$x_1^{min} - 0,6667$	$x_2^{av} - 0,6667$	Y_{i6}
7	x_1^{av}	x_2^{max}	$x_1^{av} - 0,6667$	$x_2^{min} - 0,6667$	Y_{i7}
8	x_1^{av}	x_2^{min}	$x_1^{av} - 0,6667$	$x_2^{min} - 0,6667$	Y_{i8}
9	x_1^{av}	x_2^{av}	$x_1^{av} - 0,6667$	$x_2^{av} - 0,6667$	Y_{i9}

The following formulas are applied to determine the coefficients a_i:

$$a_i = c_1 \sum_{j=1}^{N} x^j y^j, i = 1,...,n, \quad (5)$$

$$a_i = c_2[(x_{i-n}^j)^2 - \beta]y^j, i = n+1,...,2n, \quad (6)$$

$$a_i = c_3 \sum_{j=1}^{N} x_\mu^j x_\lambda^j y^j, i = 1,...,n, \mu \neq \lambda, i = 2n+1,...,k, \quad (7)$$

$$a_0 = \frac{1}{N} \sum_{j=1}^{N} y^j - \beta \sum_{j=1}^{N} a_{n+i}. \quad (8)$$

In formulas (5)–(8), c_1, c_2, c_3 are the coefficients for linear, quadratic and pair interactions of independent variables, respectively, n – the number of linear terms of the model, and N – the number of experiments.

For a polynomial of the second degree of the form (4), the values of these parameters are given in **Table 3.**

To estimate the accuracy of the obtained model, the sum of the squared deviations of the experimental values of the output variables from the calculated values obtained from the model (S_R) and the variance estimates (s^2) is calculated:

$$S_R = \sum_{i=1}^{N} (y_{exp_i} - y_{calc_i})^2, \quad (9)$$

$$s^2 = \frac{S_R}{\varphi}, \quad (10)$$

where $\varphi = N - (k+1)$ – the number of degrees of freedom, N – the number of experiments (N=9), k – the number of estimated parameters (k=5).

Table 3

The values of parameters for calculation of the coefficients of a mathematical model

N	β	C_1	C_2	C_3
9	0,6667	0,1667	0,5	0,25

Evaluation of the significance of the model coefficients is carried out on the basis of Student's t-test:

$$|a_i| \geq t_{cr} s_i, \quad (11)$$

where t_{cr} – the critical value of the Student's distribution for the confidence probability of 95 % and the number of degrees of freedom φ=3, s – the standard deviation determined on the basis of formula (10).

3. Investigation of parameters of aluminum-based DSCMs of SAP-ISML type

The input and output parameters of research are presented in **Table 4**.

Table 4

Input and output parameters of research

Input parameters	Output parameters
Al2O3 content in various SAP-ISML (x_1)	Ultimate strength (y_1)
Test temperature (x_2)	Yield strength (y_2)

Let's take Al_2O_3 content for each specific SAP-ISML type based on the average: 7 % for SAP-930, 11 % for SAP-895 and 15 % for SAP-865.

Given the lack of experimental data for the value x_2^{av}, the value of this parameter is determined by plotting the dependence on existing data using MS Excel 2010, which is acceptable, given the nature of the experimental studies (t=260 °C),

3. 1. Determination of the effect of the ultimate strength of aluminum-based DSCMs of SAP-ISML type with increasing temperature

Experimental data show that the ultimate strength in the general case tends to decrease with increasing temperature. Let's define the features of this effect, as well as the temperature (t), from which this effect becomes irreversible.

Substituting the data in (3), let's obtain a mathematical model describing the effect of Al_2O_3 content in various types of SAP-ISML, as well as the test temperature of the samples for the value of the ultimate strength. This model has the following form:

$$y = 189,4444 + 39,1745x_1 - 112,523x_2 - \\ -3,675x_1x_2 + 31,325x_1^2 - 23,75x_2^2. \quad (12)$$

Table 5 shows the results of calculations of the lower and upper limits of the intervals, which allow one to assess the significance of the model coefficients.

Table 5

Results of calculations of the lower and upper boundaries of intervals, which allow one to assess the significance of the model coefficients

Deviation values $t_{cr}S_i$		
For linear coefficients	For quadratic coefficients	For coefficients in the pair interaction
42,29307	73,24641	51,79304

Comparison of the numerical values of the estimations of the coefficients and the values given in Table 5, allow to conclude that in this model, the coefficients of quadratic interaction, pair interaction, and the coefficient at the value x_1 are insignificant coefficients. Thus, the mathematical model can be represented as:

$$y = 189,4444 - 112,523x_2. \quad (13)$$

After the mathematical model has been refined, it can be concluded that the factor "Al_2O_3 content" in the aluminum-based DSCMs of SAP-ISML type does not significantly affect the value of the ultimate strength (US).

The response surface describing the values of the ultimate strength (US) for different values of the test temperature (t) and Al_2O_3 content in the aluminum-based DSCMs of SAP-ISML type (%) in the selected planning area is shown in **Fig. 1**.

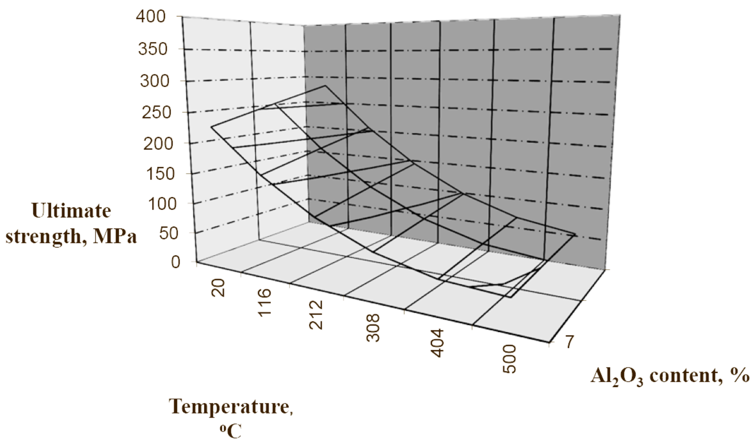

Fig. 1. The response surface describing the values of the ultimate strength (US) for different values of the test temperature (t) and Al_2O_3 content in the aluminum-based DSCMs of SAP-ISML type (%)

The visual analysis of the response surface also confirms the fact that the Al_2O_3 content has no significant effect on the ultimate strength and the only significant factor is the temperature of the test samples. Analyzing the obtained response surface, it can be concluded that the strength of the material decreases with increasing the test temperature of the sample of aluminum-based DSCMs of SAP-ISML type. It should be noted that, regardless of the Al_2O_3 content in the chosen planning area, the dependence of the ultimate strength on temperature can be represented in a linear form (13).

3. 2. Determination of the effect of the yield strength of aluminum-based DSCMs of SAP-ISML type with increasing temperature

Experimental data show that the yield strength (YS) generally tends to decrease with increasing temperature. Let's define the features of this effect, as well as the temperature (t), from which this effect becomes irreversible.

Substituting the data in (3), let's obtain a mathematical model describing the effect of Al_2O_3 content in various types of SAP-ISML, as well as the temperature of the samples for the yield strength. This model has the following form:

$$y = 144{,}1111 + 29{,}1725x_1 - 170{,}014x_2 - 1{,}995x_1x_2 + 10{,}505x_1^2 - 17{,}5x_2^2. \quad (14)$$

Table 6

Results of calculations of the lower and upper boundaries of intervals, which allow one to assess the significance of the model coefficients

Deviation values $t_{cr}S_i$		
For linear coefficients	For quadratic coefficients	For coefficients in the pair interaction
15,82712	27,41063	19,38224

Comparison of the numerical values of the estimations of the coefficients and the values given in **Table 6**, allow to conclude that in this model, the coefficients of quadratic interaction, pair interaction are insignificant coefficients. Thus, the mathematical model can be represented as:

$$y = 144{,}1111 + 29{,}1725x_1 - 170{,}014x_2. \quad (15)$$

The response surface describing the values of the yield strength (YS) for different values of the test temperature (t) and Al_2O_3 content in the aluminum-based DSCMs of SAP-ISML type (%) in the selected planning area is shown in **Fig. 2**.

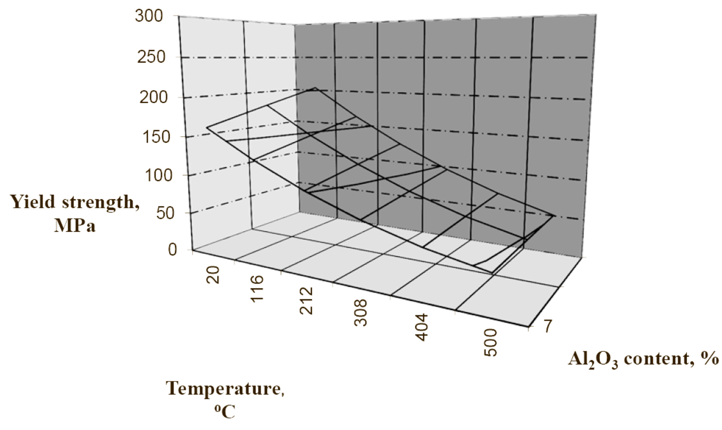

Fig. 2. The response surface describing the values of the yield strength (YS) for different values of the test temperature (t) and Al_2O_3 content in the aluminum-based DSCMs of SAP-ISML type (%)

The visual analysis of the response surface also confirms the fact that both the Al_2O_3 content and the test temperature have a significant effect on the yield strength. Analyzing the obtained response surface, it can be concluded that the yield strength increases with increasing Al_2O_3 content and decreases with increasing test temperature of the sample of aluminum-based DSCMs of SAP-ISML type.

4. Discussion of research results of the parameters of aluminum-based DSCMs of SAP-ISML type

Analysis of the response surface describing the values of the ultimate strength (US) confirms that the Al_2O_3 content has no significant effect on the ultimate strength and the only significant factor is the temperature of the test samples. Analyzing the resulting response surface, it can be concluded that the strength of the material decreases with increasing the test temperature of aluminum-based DSCMs of SAP-ISML type.

Analysis of the response surface describing the yield strength (YS) confirms that both the Al_2O_3 content and the test temperature have a significant effect on the yield strength. Analyzing the obtained response surface, it can be concluded that the yield strength increases with increasing Al_2O_3 content and decreases with increasing test temperature of the sample of aluminum-based DSCMs of SAP-ISML type.

Based on the experimental and obtained data, it can be concluded that the nature of the dependence of the yield strength and ultimate strength on temperature and Al_2O_3 content is the same. Increasing the volume fraction of Al_2O_3 can slightly increase the yield strength and ultimate strength, but this increase has a limitation related to the temperature of operation of these materials and the fact that aluminum-based DSCMs of SAP-ISML type are produced with a maximum Al_2O_3 fraction of 15 %.

5. Conclusions

As a research result, mathematical models have been constructed to determine the relationship between the chemical composition of aluminum-based disperse-strengthened composite materials of SAP-ISML type and the test temperature with the ultimate strength and yield strength values for these materials. The obtained models are regression equations, the estimated parameters of which are obtained by realizing the second order complete central orthogonal central design of the factor experiment. Analysis of these models and the resulting response surfaces shows that the ultimate strength for aluminum-based DSCMs of SAP-ISML type is most dependent on the test temperature (operation), and the Al_2O_3 content in the alloy has no significant effect.

The yield strength is almost equally dependent on both the test temperature (operation) and the Al_2O_3 content. It is established that an increase in the Al_2O_3 content and test temperature of the samples will lead to a decrease in the yield strength, and an increase in the Al_2O_3 content will increase it.

Research results can be used to select the necessary materials in the manufacture of various equipment at known temperatures of operation, as well as to make compromise optimization of the investigated parameters for controlling the quality of aluminum-based composite alloys such as SAP-ISML.

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