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VISUAL AND COGNITIVE ANALYSIS OF MULTIVARIATE DATA FOR CHARACTERIZING AL/SIC METAL MATRIX COMPOSITES

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ABSTRACT

The work shows the results of the literature review of the methods for obtaining aluminium-silicon carbide – metal matrix composites (Al/SiC MMCs). This work also includes the collection, analysis, and systemization of the literature data where textual information is presented as a single lexical and semantic system and where numeral information is presented as a dimensional system. The analysis of the literature data was conducted by visual and cognitive modelling, so that methods of forming Al/SiC MMCs and operating parameters that provide the best properties of the material (maximum level of thermal conductivity and minimum level of thermal linear expansion) are determined. Compared to the literature data, the data are presented that were received in a series of tests for obtaining Al/SiC MMCs with spark plasma sintering from SiC, which was synthesized in atmospheric electric arc plasma. Within the framework of the given subject, the authors do not know any analogues of such an analysis and visualization system that allows us to analyse multivariate data, which is essential for solving issues of finding a correlation for the variety of initial parameters that characterize the process of obtaining Al/SiC MMCs and that characterize the cluster of properties for the obtained material. The comparison data are given for thermal conductivity levels of modern (aluminium) LED light devices and Al/SiC MMC samples.

Key words: literature review, data collection, data systematization, multivariate data, visual and cognitive model, heat-transmitting element of the light device, Al/SiC MMC, properties, obtaining methods, conditions

1. INTRODUCTION

Light devices consume a large proportion of the world's electrical power generation, which constitutes about 19 % by various estimates [1]. The search for ways to reduce the energy consumption of light devices without damage to their useful quality can be considered as one of the main tasks of light engineering. Besides, the development of new and the improvement of current processes in manufacture of LEDs and LED light devices are in progress. The essential factor preventing such a development is the issue of effective heat transmission from LED light devices [2]. The use of metal matrix composite materials based on aluminium and silicon carbide (Al/SiC MMCs) in heat-transmitting elements of illumination device can solve this issue.

The most important properties of Al/SiC MMCs are a relatively high thermal conductivity factor (TCF), (100–200) W/(m·K) (standard conditions), and a low thermal linear expansion factor (TLEF), about $(8–9)\cdot 10^{-6}$ K^{-1} [3]. Thermal, physical and mechanical properties of Al/SiC MMCs significantly depend on a number of factors: SiC volume ratio; the morphology and the average size of SiC particles; the relative density and the porosity of the material; the phase composition and the grain size distribution of other impurities; the method of moulding and processing feedstock for a specific

product. The difference in directions between individual studies on obtaining and analysing properties of Al/SiC MMCs does not allow a holistic approach to form for accelerating the search of metods for this material production with the given properties of production of this material (its product) with the given properties. The comprehensive cross-disciplinary researches for properties of Al/SiC MMCs can serve as a methodological background for science-based processes in manufacture of heat-transmitting elements for power-operated electrical tools, including high power LED illumination devices [4]. A literature review on methods and properties of Al/SiC MMCs usually contains text and/or numerical data as tables and one-dimensional dependences that link pairs of individual properties of Al/SiC MMC and one of the parameters that characterize the obtaining of this material as in other review papers [3, 4]. An important issue about finding necessary regularities and prediction of material properties, including for Al/SiC MMCs, is their representation as a set of one-dimensional dependencies such as $y=f(x_1)$, $y=f(x_2)$ (etc.). However, the arguments of these functions can be characterized by physical links, including non-obvious links. The number of analysed parameters can be about 5–10. The sets of analysed parameters are not completely overlapping or complete when matching within the results of studies. As a result, a comparative analysis with the use of analytical methods is very constrained.

We offer to use visual analytics means that were successfully used in a number of practical problems for the analysis of multidimensional empirical data to overcome this difficulty [5, 21]. In this case, visual models that use features of visual perception for cognitive interpretation of multidimensional data are proposed as the means of visual analytics. The visual model is a perceptual pattern compared with the initial data on a predefined rule, a metaphor of visualization, the interpretation of which leads to an answer hypothesis to the research question. The method of visual analytic means allows performing a verification of such hypothesis with interactive control of the visual model.

The modern review works on this subject show a fragmentary nature of studies devoted, as a rule, to solution of a particular task in order to achieve the required properties of material based on Al/SiC MMCs by changing a parameter [4]. According to the published survey works in this field, it is important to conduct comprehensive cross-disciplinary researches that link the properties of products based on Al/SiC MMCs not only with the composition (chemical, phase, particle size) and the structure, but also with the method of its obtaining and the features of the applied modes. The development of a multivariate visual model for the analysis of heterogeneous data for a comprehensive assessment and a prediction for properties of Al/SiC MMCs and the development of graphic methods with a cognitive component in the analytics is light an extremely relevant goal, the solution of which is required to develop processes for creation and application of heat-transmitting elements based on Al/SiC MMCs for the use in power-operated tools, including light devices.

The method of visual cognitive analysis of multivariate heterogeneous data is applied in this work, which is information from native and foreign literature about methods of obtaining Al/SiC MMCs and their properties [5]. As a result, the model was created with Autodesk 3D Max, the validity of which was validated by obtaining Al/SiC MMCs with spark plasma sintering (SPS). However, the developed model is not intended to be based completely on information from domestic and foreign literature. This model does not have any essential restrictions for expansion of the initial data and their continuous replenishment. In such a manner, the developed model can become a new method of storage, analysis and validation of test data (in this context, data of Al/SiC MMCs) and a constantly updated alternative to occasionally conducted review researches.

2. METHODS

A feature of the initial data studied in this work is a large number of heterogeneous sources of information that are represented by publications containing information about test researches in the given field. The heterogeneity and inconsistency of information are associated with this circumstance. The search and the selection of articles from domestic and foreign publishers containing information about methods of obtaining Al/SiC MMCs and its properties were carried out during the preparation for the analysis of the initial data. It should be noted that the authors at this stage of research do not claim any completeness of the information presented in their model with reference to all key authors working

in the field of Al/SiC MMCs. The table was filled during the analysis of the literature data, containing the following fields: the record number (1); the number of the initial data source as per the reference list (2); the year of publication (3); the country of organization affiliated to the first co-author (4); the temperature T [K] at the measurement of properties for Al/SiC MMCs (5); the TCF of the material λ [$W \cdot m^{-1} \cdot K^{-1}$] (6); the TLEF δ [ppm[1]] (7); the SiC volume ratio v [%] (8); the relative density of the obtained material ρ [%] (9); the average particle size of SiC additive χ [μm] (10); the forming method of Al/SiC MMCs (11); the moulding temperature Ts [K] (12); the moulding pressure Ps [MPa] (13); the moulding time t_s [min] (14); the operating current I [A] of the moulding unit for Al/SiC MMCs (15); the data type: experimentally measured or modelled and calculated (the main part of these data is presented in Table 1).

We can see that there are three main categories of the data from the structure of the table: numerical data, text data, and absent data. The numerical data were reduced to one dimension and rounded when added to the table. If the author pointed out a range of values, the range boundaries were put in two different lines in the table. The dependence numbering was conducted by several points if there were characteristic curves not mentioned in the text of this work. The approach to the introduction of data on the bimodal distribution of SiC particles by size was not made during this research due to the fact that the division of data into two lines seems to be incorrect as the indication of the range. As a result, it was decided to indicate the arithmetical value of two modes of particle size distribution in the table. There is one similar source of information in the presented data.

The text data were added in as a result of the analysis of the lexical and semantical core of the subject: e.g. different types of impregnation (infiltration), under high pressure, in a discharged environment, and other varieties (sub-methods), were combined into a single concept of Infiltration. In addition, the search for a common textual concept was carried out. E.g. the names of the countries are given as a two-letter international code.

Dash (–) was added in case of absence of any data in the table. If any data is determined which are not relevant for the author but which obviously can

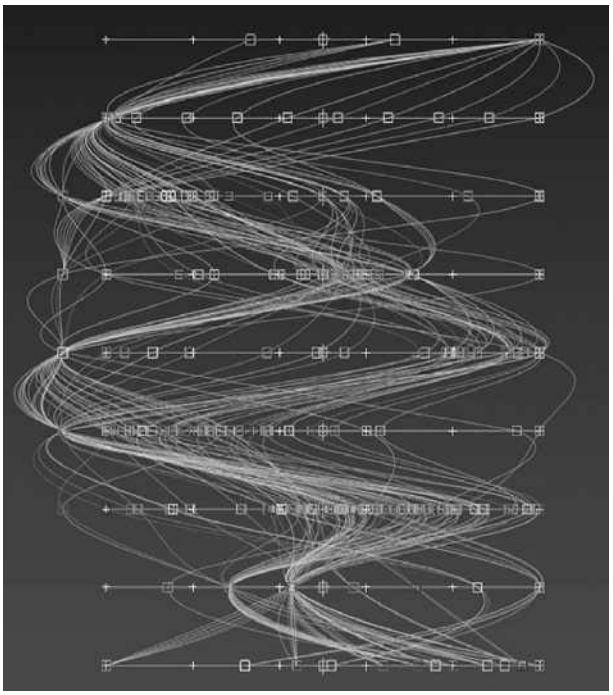

Fig. 1. The diagram of multivariate data that describes properties of Al/SiC MMCs (TCF and TLEF) depending on the method of composite forming, the volume ratio and the average size of SiC particles (year of the result included)

be deduced from the context of the work, the dependencies, and the arguments, such data were put in the relevant field. E.g. if there are no data on the temperature of Al/SiC MMCs at the measurements of the thermal conductivity, the value of the ordinary room temperature (25 °C) was taken. If experimental dependences and approximating lines were mentioned, the test points were added to the table as measured data, and the points determined from the approximated data outside the test data range were added as simulated data.

As a result of the analysis of literature sources, the data from the sources were included in the initial data table for the construction of the model [6–19]. In addition to the literature sources, this table of initial data contains the data about the test studies carried out to obtain Al/SiC MMCs with IPS using SiC obtained in atmospheric electric arc plasma [20] (cubic modification βSiC, 99 % pure, average particle size = 12μm).

The visual model created to solve the problem of the literature sources analysis (Figs. 1–3) serves as a spatial implementation of the parallel coordinates method offered for visualization of multivariate data [21]. In accordance with the visualization metaphor, a set of points in the space of the visual model united in an ordered graph is com-

[1] 1ppm = $1{,}000{,}000^{-1}$.

pared with each informative object containing published information about a separate test study. The interpretation of the information given in the visual model uses the processes of item visual comparison and such patterns of perception as the principles of constancy, integrity and generality.

The benefit of the visual model suggested in this work is simultaneous representation and reflection of different types of data in the perceived image, including multivariate data or data with missing values of some variables. The interactive control of properties of the obtained data allows defining/creating a hypothesis of the study during the analysis. This allows to repeatedly use the ready-made image (visual model) of the data, including for answers to new questions.

3. RESULT AND DISCUSSION

3.1. Al/SiC MMC Properties

Fig. 1 presents the diagram of multivariate data containing information about the properties of Al/SiC MMCs: the dependencies of the TCF and the TLEF from the composite forming method, the volume ratio, and the average SiC particle size. There is also a chronological scale for assessing the dynamic properties of the subject development over time. The timeline scale of the diagram covers the last 25 years. During the analysis of data distribution over time, we can conclude within the analysed works that the main method of forming Al/SiC MMCs was the method of infiltration 25 years ago (in its different manifestations, depending on the pressure). The infiltration moulding of Al/SiC MMCs is competing with the SPS within the analysed data during the last 15 years. SPS units that were relatively rare until the last decade are more used in the production of bulk MMCs.

According to the analysed data, TCF is (40–252) W/(m·K), mainly (118–252) W/(m·K). This range goes beyond the properties of aluminium not modified by SiC, both towards greater or less thermal conductivity. In this regard, we can conclude that the modification of aluminium with SiC does not always increase the TCF of the final composition within the framework of the presented analysed works due to the porosity of the formed Al/SiC MMC, the irregularity in the distribution of the ceramic component, its non-optimal phase and particle size distributions.

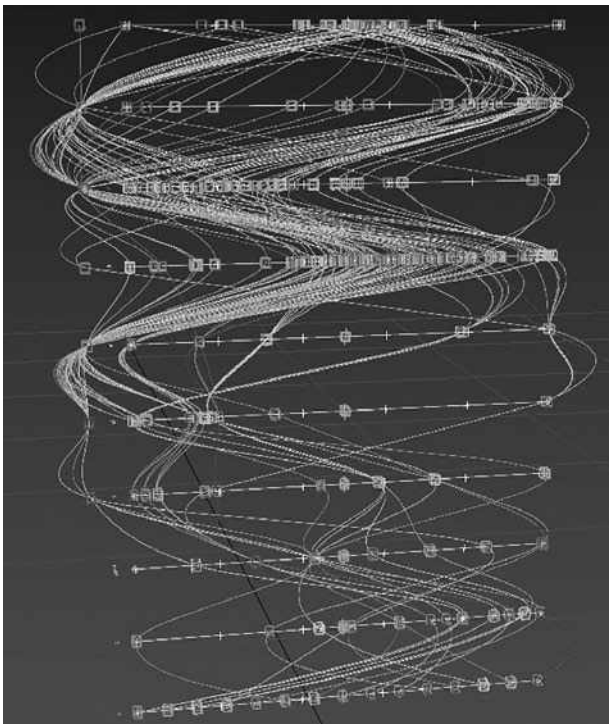

Fig. 2. The diagram of multivariate data that links the conditions and the methods of forming volume AL/SiC MMCs with some basic properties of the materials (TCF and TLEF)

We could portion the considered data array corresponding to the highest values of the TCF within the framework of the concerned model: (220–252) W/(m·K). This range of the TCF matches a series of data for the other axes that can be considered optimal to achieve the maximum TCF: density = (99–100) %, SiC volume ratio is in the range (38–70) %, average SiC particle size is equal to (100–125) μm. The parameter part determines the best quality of the material by its thermal conductivity. Some of the parameters can affect each other: e.g. the higher the volume ratio of SiC, the more difficult it is to obtain a volume material with a density of (99–100) %. According to the analysis, the part of these data is the result of calculations for the properties of the idealized Al/SiC MMC. The other part is obtained with tests.

We should note that the concerned data set that corresponds to the highest calculated and experimental levels of the TCF simultaneously matches the arguable range of TLEF values (13–17) ppm. This indicates a serious lack of knowledge in the fields of optimizing the composition, the structure and the properties of Al/SiC MMCs. The dominant majority of calculation and test works in the considered field shows the properties of Al/SiC MMCs

at normal temperatures, which do not fully reveal the potential of this composite under thermal cycling in a wide temperature range that corresponds to possible extreme operating conditions of Al/SiC MMCs.

The selection of the data array that is characterized by the lowest value of the TLEF (about 5–6 ppm) mainly matches to the TCF ranges of (150–170) W/(m·K) and the SiC volume ratio of (71–100) % (we should note that the range is represented by its boundaries, 70 and 100 %, within the model). Besides, the selection of this array corresponds to the lack of data on the density of the material (mainly) and on the average particle size of Si C. Based on the set of the analysed data on the main properties of Al/SiC MMCs, we can conclude that we cannot achieve the maximum thermal conductivity at the minimum thermal linear expansion with standard methods and with imperfect processes for the production of this composite. This problem is obviously based on the correlation between phase and particle size distributions of Al/SiC MMCs: the highest content of SiC (at the limit, up to 100 % of the SiC ratio) provides the lowest TLEF. The moulding (sintering) of the material with the dominance of the SiC ratio at the relatively low pressure and at the relatively low temperature does not ensure a high level of relative density (about (99–100) %).

The analysis of moulding conditions is given in the next subsection of this article.

3.2. Conditions and Methods for Obtaining Al/SiC MMCs

The analysis of the diagram of multivariate data (Fig.2) shows the dominance of two methods in forming Al/SiC MMCs: SPS and infiltration.

The typical sintering temperatures usually are (813–883) K at the pressures of (40–60) MPa as a part of the SPS method. The typical sintering time within this method is (5–10) min. The pressure of about 300 MPa is applied in some cases with the sintering time of up to 37 min. The highest TCF values as a part of this method are achieved at the highest pressure and with the longest sinter time, but the obtained samples have average TLEF levels of around (10–17) ppm. We can find that the potential of Al/SiC MMCs today was not implemented with the SPS method on the level of the specified properties.

Many test samples were obtained with infiltration. The process usually flows at the temperatures of (973–1173) K that are higher than with the SPS method and at the relatively low pressures: about (1–2) MPa, in some cases up to 10 MPa. The process time is about 30 min. From all the works we analysed, we can single out the work [7] where the minimal TLEF of (5–6) ppm corresponds to the TCF of (225–250) W/(m·K) . These samples were obtained at the highest pressure we considered, 10 MPa, and at the relatively low temperature of 1023 K. The volume ratio of SiC was about 70 % in the sample. The parameters of the above test can be considered close to the optimum within the infiltration method. However, the work [7] has a number of other features: the authors first sintered SiC to a continuous 3D (volume) porous structure at 2673 K. As a result, the issue of the average size of the particles in the sample is ambiguous. SiC is represented in pictures taken by a focused beam microscope (within the resolution limits) in the form of a continuous monolithic structure. After such a structure, the pores in the sample are filled with molten aluminium at a pressure of the environment gas of 10 MPa.

On the one hand, this approach allowed us to keep the smallest TLEF, which was ensured by a frame of continuous integral (polycrystalline – as we can see) substance of SiC, the pores of which are filled with molten aluminium. The relative density of the sample is not specified in the work [7] due to the complexity of its determination in the chosen synthesis approach. We can conclude that the achievement of good properties is possible during the infiltration method for Al/SiC MMCs at the low TLEF of (5–6) ppm and at the TCF up to about 250 W/(m·K) with the SiC ratio of about 70 %. However, the variety of this method, which provides excellent key figures, is relatively complex and consists of several stages where a continuous volume porous structure of SiC plays a key role.

3.3. Test Research for Obtaining Al/SiC MMCs with the SPS

4 samples of Al/SiC MMCs were sintered within this work that had different weight fractions of SiC (2.5, 12.5, 25.0 and 50.0 %) with the SPS (through SPS10–4 by GT Advanced Technologies, USA). The basic substance was the powder of the

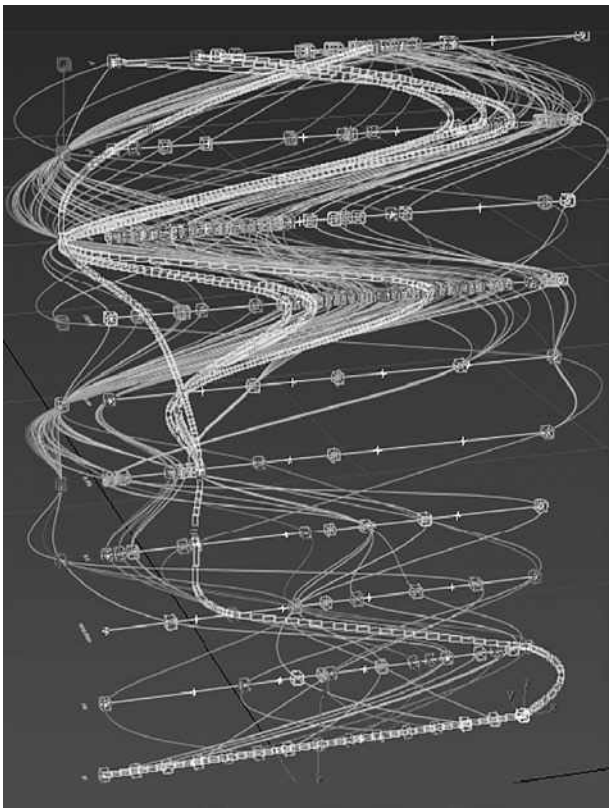

Fig. 3. The diagram of multivariate data that links the conditions and the methods of forming volume AL/SiC MMCs with some basic properties of the materials (TCF and TLEF) to compare our test data with the information from the literature sources

SiC cubic phase (βSiC) with an average particle size of about 12 μm and the commercial aluminium powder. SiC was obtained in the direct-current arc atmospheric plasma with the method developed at the National Research University – Tomsk Polytechnic University. The samples were sintered at the temperature of 833 K for 10 min and at the pressure of 60 MPa. The samples were studied with an X-Ray Diffractometer Shimadzu XRD7000s, a Scanning Electron Microscope Jeol JSM 5700F and a Laser Thermal Conductivity Meter TA Instruments-DLF 1200.

Based on the data in Fig. 3 that are in the form of the visual and cognitive analysis, the results were experimentally obtained and they corresponded to the results that are typical for the SPS: The TCF was (115–190) W/(m·K) for three samples with a lower SiC ratio and about 55 W/(m·K)[1] in a sample with the highest SiC ratio. Such levels of thermal conductivity, the applied method and the mode parameters are consistent with the worldwide-published data with due regard to phase and particle size compositions of the obtained images.

3.4. Assessment for Applications of Heat-Transmitting Elements Based on Al/SiC MMCs in Illumination Tools for the Achieved Thermal Conductivity

The aluminium-based radiators that are used for LED device cooling can feature the TCF of (150–200) W/(m·K) [22, 23]. The modern domestic and foreign heat-transmitting elements that are based on Al/SiC MMCs can feature the TCF of (150–170) W/(m·K) (some foreign elements can achieve up to 200 W/(m·K)) [15]. According to the studied literature sources, the highest achieved TCFs of Al/SiC MMC samples are (220–252) W/(m·K), which is higher than the TCFs of typical aluminium radiators used for LED cooling. Such a level of thermal conductivity allows for reliable and long-term operation of a single LED50 W or a group of close-packed LEDs, each 3 W [22, 23]. The heat-transmitting elements based on Al/SiC MMCs are suitable for use in LED illumination devices. The relatively low TLEF of high-filled Al/SiC MMCs allows for use of the tools in extreme ranges of thermal cycling, e.g. in the Arctic.

4. CONCLUSION

The collection, the systematization and the analysis of literature sources were made in this research that concern the methods of obtaining Al/SiC MMCs, their properties, the properties of heat-transmitting elements of LED illumination devices. The feature of this study is the approach that is based on a visual and cognitive model, which contains an array of multivariate heterogeneous text and numerical data. The developed visual model allowed: 1) to show the multivariate heterogeneous data with the use of the cognitive capacity of the user; 2) to identify the properties of the most common synthesis methods for Al/SiC MMCs (within the existing literature), the operating moulding parameters, as well as the phase and particle size distributions that provide the best results for the TCF and the TLEF. The model also included the data that were obtained during the test study of Al/SiC MMCs, which confirmed the main literature data. The visual model also allowed us to create new hypotheses to study the obtaining methods for Al/SiC MMCs and their properties. The authors today do not know any cases of such approach to the processing, the analysis and the storage of data on certain materi-

Table 1. The Main Data Used for Modelling*

Literature Source	λ, W/(m·K)	δ, ppm	v, %	ρ, %	x, µm	Molding Method	Ts, K	Ps, MPa	ts, min
[6]	210	24	0	100	–	–	–	–	–
	239	17	40		110	SPS	873	300	37
	247	15	45						
	252	14	50						
	246	13	55	99					
	208	12	60	98					
	–	10	70	–	–				
	–	5	100	–	–				
[7]	182	9	46	–	–	Infiltration	1023	10	–
	250	7	54	–	–				–
	250	6	63	–	–				–
	225	5	70	–	–				–
	140	10	46	–	–				–
	175	9	54	–	–				–
	180	8	63	–	–				–
	170	7	70	–	–				–
[8]	130	11.2	50	99	23	*Hot press*		55	15
	135	11.6		99	38				
	141	12.1		97	75				
	140	10.8		99	23				
	148	11.2		99	38				
	156	11.5		97	75				
[9]	38.5	–	50.4	97	8	Plasma spraying	–	–	–
	50.6	–	52.7	98	11		–	–	–
	69.8	–	51.6	98	17		–	–	–
	71.4	–	38.8	99	30		–	–	–
[10]	153	–	–	–	0.3	Infiltration	973	0.4	–
	155	–	–	–					–
	154	–	–	–					–
	156	–	–	–					–
	157	–	–	–					–
	162	–	–	–					–
	163	–	–	–					–
[11]	200	23	0	–	–		–	–	–
	170	16.4	25	–	–		–	–	–
	135	10.4	55	–	–		–	–	–
	105	6.2	70	–	–		–	–	–
	80	5	100	–	–		–	–	–

Literature Source	λ, W/(m·K)	δ, ppm	v, %	ρ, %	x, µm	Molding Method	Ts, K	Ps, MPa	ts, min
[12]	221	–	58	–	167	Infiltration	1023	0.28	30
	209	–	58	–	86.4			0.34	
	203	–	60	–	56.8			0.40	
	204	–	59	–	37.1			0.50	
	194	–	58	–	23.4			0.60	
	193	–	55	–	16.9			0.78	
	154	–	53	–	8.9			2.1	
[13]	190	–	0	–	100		–	–	–
	225	–	70	–			–	–	–
	237	–	70	–			–	–	–
	180	–	–	–	20		–	–	–
	210	–	–	–	50		–	–	–
	220	–	–	–	200		–	–	–
[14]	208	–	55	100	40	SPS	833	50	5
	211	–	60	100			833	50	
	204	–	58	97.4			833	45	
	185	–	56	92.8			833	40	
	192	–	56	93.7			823	45	
	165	–	53	87.5			813	40	
	220	–	50	100	100		833	50	
	224	–	55	100			833	50	
	208	–	58	96.3			833	45	
	197	–	55	91.2			823	40	
	181	–	53	88.7			813	45	
	173	–	52	86.6			813	40	
[15]	158	4.97	70	–	125	Infiltration	–	–	–
	162	5.14		–			–	–	–
	161	5.32		–			–	–	–
	156	–		–			–	–	–
	154	5.97		–			–	–	–
	150	6.31		–			–	–	–
	149	–		–			–	–	–
[16]	177	9.5	50	98.9	48	Casting	1073	50	–
	172	7.89	58	99.3	48				–
	138	7.74	71	97.5	28**				–
	125	6.33	71	97.8					–
	123	6.54	71	97.1					–
[17]	165	9.2	70	–	40			100	–

Literature Source	λ, W/(m·K)	δ, ppm	v, %	ρ, %	x, µm	Molding Method	Ts, K	Ps, MPa	ts, min
[18]	190	10	50	–	28	Infiltration	1073	50	–
	125	7.5	70	–	28				–
	150	6		99.5	–				–
	140	7.5		99	–				–
	135			98	–				–
	120			97	–				–
[19]	146	10.5	39	99	6		1173	0.1	–
	136	9.24	52						–
	118	8.45	62						–
–	188	–	0	98	12	SPS	883	60	10
–	120	–	16.9	96					
–	131	–	21.4	97					
–	54	–	53.6	86					

* The data in the table may differ from the data given in the sources due to the conversion into a single system of dimensions, rounding and adding to the table the data that are the conclusion of the authors of this work based on the analysis of the primary source.
** The given value is the arithmetic mean value of the limits for the bimodal particle size distribution.

als, their properties, methods and operating parameters of their production. They also believe that the method of visual and cognitive modelling is applicable to solve any search-related analytical problems in different subject fields.

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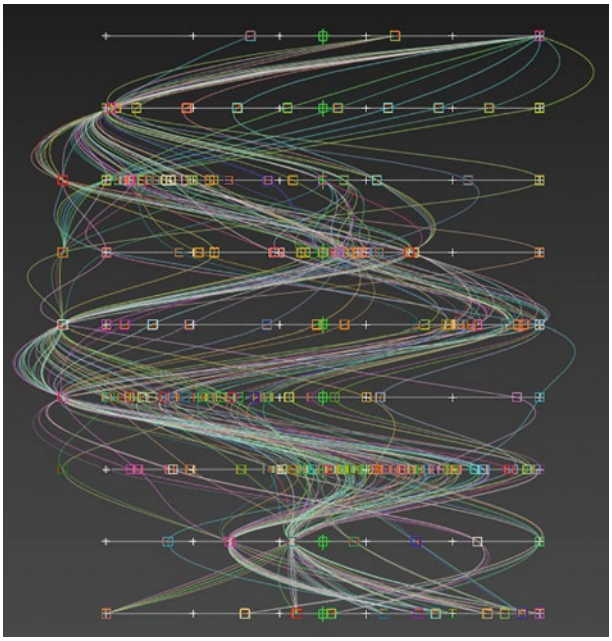

Fig. 1. The diagram of multivariate data that describes properties of Al/SiC MMCs (TCF and TLEF) depending on the method of composite forming, the volume ratio and the average size of SiC particles (year of the result included)

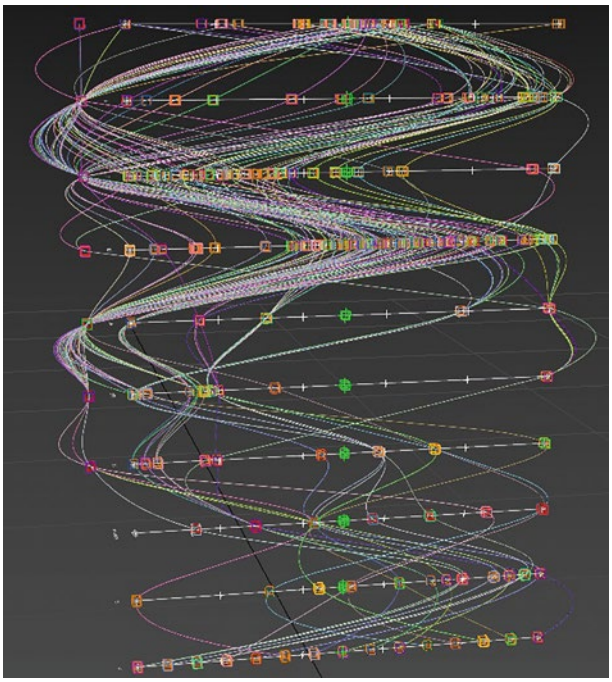

Fig. 2. The diagram of multivariate data that links the conditions and the methods of forming volume AL/SiC MMCs with some basic properties of the materials (TCF and TLEF)

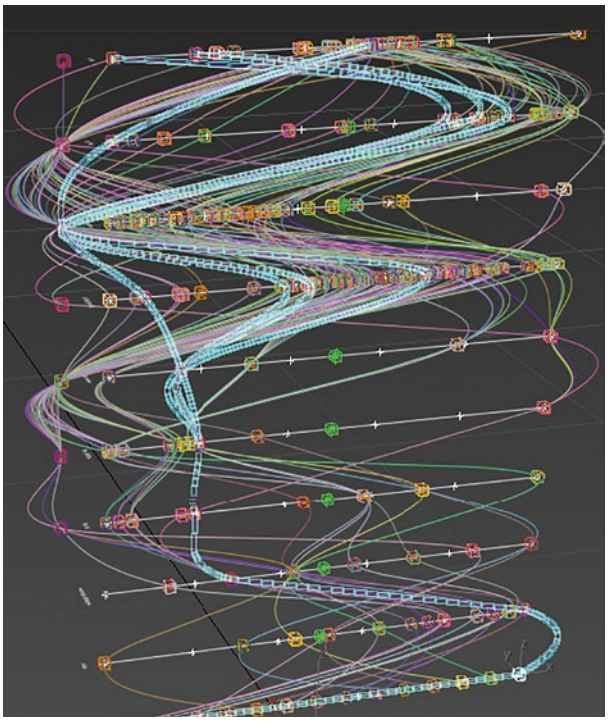

Fig. 3. The diagram of multivariate data that links the conditions and the methods of forming volume AL/SiC MMCs with some basic properties of the materials (TCF and TLEF) to compare our test data with the information from the literature sources