

## REPORT OF THE OFFICIAL OPPONENT

on Tan Kun's dissertation

on the topic "Development of supersonic nozzles for cold spraying",

applied for the degree of Doctor of Philosophy

in the field of knowledge 13 Mechanical Engineering

in the speciality 134 Aerospace Engineering

### Relevance of the Dissertation Topic.

Cold gas dynamic spraying technology is a new type of additive manufacturing technology, often used in coating preparation. It can prepare target coatings on the surface of parts or repair damage on the surface of parts. It is widely used in the field of aerospace surface engineering technology. By improving equipment components and optimizing spraying patterns to form coatings from given powder materials, the productivity of the process can be improved, and high-performance indicators of coating quality can be ensured. Spraying complex external surface parts or difficult-to-reach surfaces inside parts depends mainly on the cold spray nozzle structure. Therefore, based on the traditional linear cold spray nozzle, further exploring the new structure of the cold spray nozzle is a significant work. The deposition time of powder particles on the substrate is very short. Therefore, the deposition process of powder particles on the substrate is studied by numerical simulation to more accurately understand the deformation of powder particles after hitting the substrate and the formation process of coating; it is an important work to study the influence of spraying parameters on the porosity of coating by numerical simulation.

### Evaluation of the Scientific Validity, Credibility, and Novelty of the Dissertation's Research Findings.

The scientific propositions, conclusions, and recommendations developed by the author and presented in the dissertation are sufficient to be valid. The results of the performed research are based on known achievements in the subject field and do not contradict theoretical laws, known facts and generally accepted ideas about the gas dynamics of two-phase flow and the mechanics of high-speed collision of a solid body with a surface.

The author used modern theoretical and numerous modeling methods. The theoretical part of this dissertation uses computational fluid dynamics, gas dynamics and finite element numerical analysis of solid-liquid two-phase flow composed of micron particles and gas. The multi-parameter coupling optimization of the powder particle velocity uses the response surface analysis method and GA+BPNN method. Among them, numerical simulation uses the SPH, ALE and CEL methods to simulate the deposition of single particles/multi-particles on the substrate. Solidworks, Caxa, and Python programming codes are used to establish the Al6061 multi-particle model; the response surface analysis method is used to optimize the coating porosity.

The validity and reliability of the scientific results of the dissertation have been confirmed by their approval at international scientific and practical conferences, the papers of which are indexed in the N.M.B.D. Scopus. Also, some scientific results of the acquirer were verified within the framework of the National Research



Development Program "Development of a complex technology for restoration and repair of aviation (helicopter) equipment parts by cold gas-dynamic spraying with subsequent cutting processing" (No. DR 0122U001341, 2020-2022), which was carried out at the Department of Technology of aircraft engine production of the National Aerospace University named after M. E. Zhukovsky "Kharkiv Aviation Institute".

The author presented very interesting scientific results. The scientific novelty of the results of the thesis is as follows:

1) *for the first time*, a method of profiling supersonic single- and multi-channel right-angle nozzles for cold gas-dynamic spraying of coatings on internal and out-of-view surfaces was proposed, which provides the necessary values of the speed of powder particles at the exit of the nozzle for their adhesion to the substrate when the flow is turned by 90°.

2) *for the first time*, based on the results of numerical modeling, the dependence of the temperature-velocity characteristics of the powder particles at the exit from the right-angle nozzle on the material of the particles, their size, temperature and gas pressure at the entrance to the nozzle was obtained.

3) *for the first time*, an approach to assigning cold gas-dynamic spraying modes is proposed, based on the planning of a multi-factor experiment, response surface methodology and GA+BPNN, which allows assigning the technological parameters of coating sputtering, which ensure that the powder particles achieve the speed necessary for their adhesion to the substrate.

4) *for the first time*, on the basis of numerical modeling and the planning methodology of a multifactorial experiment, the dependences of porosity on particle speed, its temperature, and the temperature of the substrate in the studied ranges of values were obtained.

So, the scientific task set in the dissertation work was completely fulfilled, and the winner fully mastered the methodology of scientific activity.

#### Assessment of the Dissertation Content, Its Completeness, and Adherence to the Principles of Academic Integrity.

The dissertation of Tan Kun fully complies with the Standard of Higher Education in speciality 134 Aerospace Engineering and corresponds to the areas of scientific research in accordance with the relevant educational program.

The presented dissertation was completed at a high scientific level and is a fully completed scientific work.

The author's personal contribution to all areas of research and results in cold spray technology is unquestionable. Based on the report on the originality of the dissertation, it can be concluded that Tan Kun's dissertation is the result of independent research and does not contain elements of falsification, compilation, fabrication, plagiarism or borrowing. The ideas, results and texts of other authors in the dissertation have appropriate links to sources.

The dissertation consists of an abstract, introduction, 4 chapters, conclusions and an appendix. The total volume of the dissertation is 273 pages, of which 226 pages



are the main text. The dissertation contains 83 figures, 38 tables, 190 references and an appendix.

The Introduction provides the rationale for choosing the research topic and its significance, as well as the object, subject, purpose and objectives of the research, as well as the relationship of the work with scientific topics, scientific novelty and practical results of the research and its validation.

The first chapter provides an overview of the current state of the researched problem and publications, the main focus of which is aimed at solving the problems of the dissertation work, in particular, the use of numerical modeling methods to study the gas dynamics of two-phase flow in supersonic nozzles for cold gas dynamic spraying, and the study of the processes of interaction of powder particles with the substrate at high-speed depositions and formation of coatings. From the analysis of the publications, it was concluded that there is no comprehensive approach to the design of nozzles, as well as the optimization of the parameters of the cold gas-dynamic spraying process according to the criterion of particle speed at the moment of deposition with the substrate.

The second chapter gives the main equations for describing the gas-dynamic features of the flow in supersonic nozzles for cold gas-dynamic spraying, which are used in the design of narrowing-expanding nozzles for spraying. A description of the phenomena that occur during the interaction of a powder particle with a surface during spraying is also presented. The models describing the interaction of a powder particle with a substrate, which are used for numerical simulation of high-speed deposition of a particle with a surface for homo- and heterogeneous materials are analyzed.

The third section presents the results of the development of a narrowing-expanding nozzle of optimal geometry. the influence of nozzle expansion section length on particle acceleration characteristics was investigated by single factor analysis, and suggestions for improvement were proposed. The spraying of some complex external surface parts or hard-to-reach surfaces inside parts depends largely on the cold spray nozzle structure. Therefore, based on the traditional linear cold spray nozzle, right-angle cold spray nozzles and multi-channel mixed cross-section right-angle nozzles were further explored and developed. The acceleration process of powder particles in these nozzle channels was studied, which depends on the spraying pattern and characteristics of the powder and the scheme of feeding the powder into the nozzle. Based on the multi-criteria analysis using the experimental planning method, the response surface method of the powder particle velocity on a large range of spray parameters was constructed. Based on the maximum velocity criterion of the particles at the nozzle outlet, scientific recommendations were made for the selection of the spraying pattern of the proposed nozzle for the studied powders.

The fourth chapter presents the results of numerical modeling of the high-speed interaction of powder particles with the substrate at the moment of deposition for homo- and heterogeneous materials during cold gas-dynamic spraying. Taking Al6061 coating as an example, the SPH, the ALE, and the CEL methods are used to simulate the deposition of single particle, and a comparative analysis is conducted on the three methods mentioned above. The temperature-velocity characteristics of powder particles when contacting the substrate and the influence of substrate temperature on the degree of particle deformation according to the input particle



deformation coefficient  $K$  are proposed. The deformation coefficient  $K$  can be used to characterize the particle deformation. The establishment of a multi-particle model is realized through Python programming code, and the CEL method is suggested to simulate the deposition of multiple particles, so as to optimize the spraying mode. This method realizes the monitoring of the coating porosity, and the response surface analysis method is used to optimize the coating porosity.

Conclusion briefly describes the main results of the research of the dissertation and proposes promising tasks for possible further research.

Appendix is a multi-particle model established using Python programming code.

The dissertation adheres to the requirements outlined in the order of the Ministry of Education and Science of Ukraine dated January 12, 2017, No. 40, "On Approval of the Requirements for the Dissertation Formatting".

#### Language and Style of Presenting the Results.

The dissertation has been written in English and presented consistently, in a scientific style, using generally accepted terminology. The dissertation material, description and mathematical calculations are laid out consistently, logically and in an accessible form. For all abbreviations that are not generally accepted or little-known, transcriptions are provided at the first mention in the text.

#### Publication of Dissertation Results.

The results of the dissertation work were published in 20 articles. Among them 5 articles in scientific periodical publications included in category «A» of the List of scientific specialized publications of Ukraine, or in foreign publications indexed in the Web of Science Core Collection and/or Scopus database; 8 articles in scientific periodical publications included in the List of scientific specialized publications of Ukraine (category «B»); and 7 conference proceedings (5 of them indexed in the Scopus database). Thus, the scientific results described in the dissertation are fully explained in the scientific publications of the acquirer.

#### Remarks and comments on the thesis contents.

1. In the thesis, the calculation of the geometric dimensions of supersonic nozzles for spraying was performed. Still, it was not clearly stated which criterion was used for nozzles geometry optimization.

2. The author notes in the first chapter that currently, depending on the working pressure of the gas, there are two types of cold gas-dynamic spraying – high and low, but it is not justified why the dissertation focuses on nozzles for high pressure.

3. In the thesis the results of multifactor optimisation of cold gas dynamic spraying modes are presented, however, the justification of the choice of the investigated parameters as well as the intervals of their variation is not sufficiently complete..

4. There is no justification for choosing powder and substrate materials for high-speed collision simulation in the dissertation.



5. The acquirer introduced the deformation coefficient of an individual particle when it collides with the substrate, but the impact of subsequent particles arriving on it, which additionally deform the first one, is not considered.

I believe that the comments expressed are not decisive, don't reduce the general scientific novelty and practical significance of the results and don't affect the positive evaluation of the dissertation work, but are aimed at further research in this area.

Conclusion on the dissertation.

The dissertation work of the applicant for the scientific degree of Doctor of Philosophy Tan Kun on the topic "Development of supersonic nozzles for cold spraying" is a fully completed work at a high scientific level. The applicant adhered to the principles of academic integrity. The presented dissertation work is a comprehensive scientific study that solves a research problem that is important for the field of Knowledge 13 Mechanical Engineering. The dissertation work is relevance, practical value, and scientific novelty, fully meeting the requirements of the current legislation of Ukraine as outlined in paragraphs 6-9 of the "Procedure for awarding the degree of Doctor of Philosophy and revoking the decision of a one-time specialized academic council of a higher education institution, research institution, on awarding the degree of Doctor of Philosophy," approved by the Resolution of the Cabinet of Ministers of Ukraine on January 12, 2022, No. 44.

I am confident that the co-applicant Tan Kun deserves to be awarded the degree of Doctor of Philosophy in knowledge area 13 Mechanical Engineering, speciality 134 Aerospace Engineering.

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