

REPORT OF THE OFFICIAL OPPONENT

on Hu Wenjie's dissertation
on the topic "Cold spraying of protective and restorative coatings on parts of
aviation engineering made of titanium alloys",
applied for the degree of Doctor of Philosophy
in the field of knowledge 13 Mechanical Engineering
in the speciality 132 Materials science

Relevance of the Dissertation Topic.

The topic of Hu Wenjie's dissertation, "Cold spraying of protective and restorative coatings on parts of aviation engineering made of titanium alloys", is relevant because cold gas dynamic spraying is an emerging coating preparation process technology that has developed in recent years. It is a part of surface additive manufacturing and repair technology suitable for the field of aerospace technology. Research and exploration of cold gas dynamic spraying technology can better and more widely develop the application of this technology.

The relevance and necessity of research are due to the development of cold gas dynamic spraying technology in the field of surface engineering and the use of technology to create volumetric additive materials. Increasing the productivity of the process and ensuring high-performance indicators of coating quality can be achieved by improving equipment elements and optimizing spraying modes for forming coatings from given powder materials. In addition, the expansion of technological capabilities of equipment for spraying coatings on internal and hard-to-reach surfaces of parts will open new directions for the practical application of technology in spraying protective and restorative coatings.

The aim of the research is to improve the cold gas dynamic spraying of coatings technology on titanium alloys by establishing the optimal geometry of the spraying nozzles, the regularities of the influence of gas parameters at the nozzle entrance and powder characteristics on the speed of particles at the moment of impact with the substrate.

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 research results are based on known achievements in the subject field and do not contradict theoretical laws, known facts and generally accepted ideas about the cold 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 modelling methods. The theoretical part of this dissertation uses computational fluid dynamics, gas dynamics, and finite element numerical analysis of solid-liquid two-phase flows consisting of micron particles and gases. Multi-parameter coupling optimisation of the velocity of powder particles uses the response surface analysis method and GA+BPNN method. The SPH method has done a lot of new numerical simulation work, and the research results are accurate compared with those of other workers.

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 Web of Science Core Collection and/or Scopus databases. Also, some scientific results of the acquirer were verified within the state budget research project of the Ministry of Education and Science of Ukraine "Development of aggregate technology of restoration and repair of aviation (helicopters) parts by cold spraying with post process machining of deposited coatings" (№ ДП 0122U001341, 2022-2023) and "Development of technology and equipment for cold spraying of restorative coatings on aircraft parts" (№ ДП 0124U000553, 2024).

The scientific novelty of the dissertation's research is as follows:

1) for the first time, based on the results of numerical modelling, the dependence of the speed of a powder particle at the exit from a profiled single-channel nozzle for spraying on the gas parameters at the nozzle entrance (temperature and pressure), powder characteristics (material and particle size), and geometric characteristics of the nozzle (diameter of the critical section, its length, the angle of rotation of the flow in the critical section, the length of the expanding part of the nozzle, the powder supply point).

2) for the first time, the features of the acceleration and trajectory of the movement of powder particles in the profiled rotating nozzle were determined depending on the temperature and pressure of the main gas flow, the pressure of the transporting flow, the material of the powder and the size of its particles.

3) A scientifically based comprehensive approach was further developed, which is based on the use of theoretical calculations and the results of numerical modelling and makes it possible to predict the speed of particles of various powder materials at the exit from the nozzle, which made it possible to obtain and generalize the ways of ensuring the formation of bonds between powder particles and substrate.

So, the scientific task set in the dissertation work was completely fulfilled, and the author 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 applicant Hu Wenjie fully complies with the Standard of Higher Education in speciality 132 Materials science and corresponds to the areas of scientific research in accordance with the relevant educational program.

The presented dissertation work 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 dissertation's originality, it can be concluded that Hu Wenjie'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.

Language and Style of Presenting the Results.

The dissertation has been written in English and presented consistently, scientifically, 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.

The dissertation consists of an abstract, 4 chapters, conclusions and appendices. The total volume of the dissertation is 186 pages, of which 177 pages are the main text. The dissertation contains 96 figures, 34 tables, 171 references and 2 appendices.

The introduction substantiates the relevance and necessity of the chosen research direction, formulates the goal and task of the research, outlines the scientific novelty and practical significance of the obtained results, and provides information about their approval, publications and the structure of the dissertation work.

The first chapter examines the use of titanium alloys in the aviation and aerospace industries, operational defects, their causes, and possible ways of prevention and elimination. Methods of applying coatings, the place among them of cold gas dynamic spraying, and its advantages and prospects regarding the possibilities of use for obtaining coatings on titanium alloy surfaces are given. Special attention was paid to the analysis of the influence of parameters of cold gas-dynamic spraying on the properties of coatings and the efficiency of the process. An analysis of publications dedicated to using technology for spraying

wear-resistant coatings on titanium alloys and materials used to restore the worn surfaces of parts from these alloys was conducted. Based on the analysis results, unsolved issues in cold gas-dynamic spraying of coatings on titanium alloys were identified, and ways of solving them and improving the technology were outlined.

In the second chapter, the main equations of gas dynamics are given, describing the flow in narrowing-expanding nozzles for cold gas dynamic spraying and calculating their geometric characteristics. The models were analysed to find powder particles' temperature-velocity characteristics in the nozzle channel gas flow. The results of the development of a direct supersonic nozzle for spraying are presented, as well as the results of numerical modelling of the influence of the geometric parameters of the nozzle (the diameter of the critical section of the nozzle, its length, the angle of rotation of the axis of the nozzle in the critical section), as well as the material of the powder and the size of the particles on their velocity at the exit from nozzle using the method of multi-factorial planning of the experiment, the complex influence of gas parameters (pressure and temperature) at the entrance to the nozzle and the diameter of the powder particles on their velocity at the exit from the nozzle for the selected geometry of the rotary single-channel nozzle was investigated. The regression equation for predicting the speed of particles depending on the studied parameters is obtained, and recommendations for choosing the optimal modes that ensure obtaining the maximum speed of powder particles are given. A rotary nozzle for spraying coatings on interior and hard-to-reach surfaces was developed and studied using numerical simulation. The optimal minimum length of the rotating expanding part of the nozzle was determined to ensure the required speed of the particles at its exit. The simulation results of the influence of this nozzle's geometric characteristics on the powder particles' acceleration and speed at the moment of contact with the substrate are given. Dependencies are built, and recommendations are given for choosing the radius of rotation of the nozzle, the length of the extended part and the distance of spraying to ensure the maximum values of the velocity of the particles at the moment of contact with the surface of the substrate. A multi-channel rotary nozzle is offered for cold spraying on surfaces of internal and hard-to-reach parts. The effect of particle diameter, pressure of the gas transporting the powder, channel dimensions, recovery coefficient, and powder material on the acceleration and trajectory of particle movement in and out of the nozzle was studied. The results of numerical modeling obtained for determining the speed of particles in the developed rotary nozzle were compared with the values of the critical spraying speed for the studied materials, and conclusions were made regarding the possibility of forming coatings from them.

The third section of the dissertation is devoted to the numerical modelling of the process of high-speed collision of powder particles with the substrate in the process of cold gas-dynamic spraying. For the first time, the use of the criterion Y (the ratio of the depth of the crater in the surface, formed as a result of the collision of a powder particle with it, to the height of the deformed particle) is proposed, which can be used to determine the critical speed of the particle at the moment of collision, necessary for its adhesion to the surface and to predict the possibility of formation adhesive bonds between them. The results of studies of the collision of a single particle with a surface for homo- and heterogeneous materials in a wide range of particle velocities are given, and recommendations are given for choosing the values of the criterion Y and the corresponding values of the particle velocity for different materials that ensure the formation of bonds and the formation of coatings. The simulation results are compared with the calculated values of the critical speed and the results of other scientists. The process of collision of powder particles of various materials with a titanium surface is considered from the point of view of energy balance for a better understanding of the influence of the particle speed at the time of collision with the substrate on the process of cold gas dynamic spraying. When spraying on a titanium alloy surface, the results of the numerical simulation of the collision of a set of particles of a pure metal powder, as well as a powder mixture.

The fourth chapter provides recommendations for the practical use of the obtained results of the dissertation work, in particular, the geometry of the channels of supersonic nozzles for cold spraying of direct and rotary spraying coatings on the inner surfaces of parts made of titanium alloys, the developed device for feeding powder into the extended part of the nozzle during cold high-pressure spraying, selection of spraying parameters (pressure and temperature of the gas at the entrance to the nozzle, the size of the powder particles), which ensure that the particles achieve the speed values necessary for their adhesion to the surface and the formation of the coating. Recommendations for further studies of the cold gas dynamic spraying process are given.

The conclusion briefly describes the main results of the dissertation research and proposes promising tasks for further research.

The appendixes represent Abaqus software guide that simulates key particle deposition processes and the list of publications in this dissertation.

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".

Publication of Dissertation Results.

The results of the dissertation work were published in 19 articles. Among them 7 articles in scientific periodical publications included in category «A» of the List of scientific specialized publications of Ukraine, or in foreign publications indexed on the Web of Science Core Collection and/or Scopus database; 6 articles in scientific periodical publications included in the List of scientific specialized publications of Ukraine (category «Б»); 5 conference proceedings (4 of them indexed in the Scopus database), and 1 Chinese patent.

Thus, the scientific results described in the dissertation are fully explained in the scientific publications of the acquirer.

Disadvantages and comments to the dissertation work.

1. In sub-section 2.2.3, the author presented the results of the influence of the geometric parameters of the convergent-divergent cold spray nozzle, particularly the diameter of the throat, on the velocity of particles at the nozzle exit. However, it is worth noting that the diameter of the critical cross-section affects the gas flow rate through the nozzle, which is not mentioned in the dissertation and is mainly used as a criterion of optimality when developing a nozzle for spraying.

2. The proposed single-channel 90° nozzle shown in Fig. 2.23 has a rectangular channel shape, but all previous simulations on the effect of geometry and the recommendations given have been performed for a nozzle with a circular channel shape.

3. Research on the effect of the length of the gas supply channel on the gas velocity at the nozzle exit (sub-section 2.4.2.3) with the constant convergent part does not make sense since, from a practical point of view, it is only a matter of maintaining the temperature of the gas flow from the gas heater.

4. In the multi-channel nozzle proposed by the applicant (fig. 2.38), structural elements are used to turn the flow in the nozzle channel, the dimensions of which raise doubts about the possibility of their manufacture.

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 work.

The dissertation work of the applicant for the scientific degree of Doctor of Philosophy Hu Wenjie on the topic “Cold spraying of protective and restorative coatings on parts of aviation engineering made of titanium alloys” 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.

The applicant Hu Wenjie deserves to be awarded the degree of Doctor of Philosophy in the field of Knowledge 13 Mechanical Engineering, in the speciality 132 Materials science.

Official opponent:

Doctor of Technical Sciences,
Professor,
Dean of the Faculty of Physics and
Technology,
Oles Honchar Dnipro National
University

Anatolii SANIN