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Wojciech MIZAK, Adam MAZURKIEWICZ
Institute for Sustainable Technologies – National Research Institute, Radom, Poland
wojciech.mizak@itee.radom.pl; adam.mazurkiewicz@itee.radom.pl

SYSTEM FOR NONSTANDARD TESTING OF EROSIVE WEAR OF MATERIALS

Key words: surface engineering, erosion, nonstandard testing, research methodology.

Abstract: The article presents a systemic approach to erosive wear testing that allows nonstandard erosion tests of construction and functional materials to be carried out in a wide range of variability of the erosion process parameters, and the testing system allows the identification of phenomena occurring during impact erosion. The methodology and a unique device for the simulation of the erosive wear process included in the developed research system were presented. The results of verification tests of the authors' system for nonstandard testing of erosive wear of construction and functional materials are also shown in the article.

System ponadnormatywnych badań zużycia erozyjnego

Słowa kluczowe: inżynieria powierzchni, erozja, badania niestandardowe, metodyka badań.

Streszczenie: W artykule zaprezentowano systemowe podejście do badań zużycia erozyjnego umożliwiające przeprowadzenie niestandardowych testów erozyjnych materiałów konstrukcyjnych i funkcjonalnych realizowanych w szerokim zakresie zmienności parametrów procesu erozji oraz pozwalające na identyfikację zjawisk zachodzących podczas erozji uderzeniowej. Przedstawiono metodykę i unikatowe urządzenie do symulacji procesu zużywania erozyjnego wchodzące w skład opracowanego systemu badawczego. Zaprezentowano wyniki badań weryfikacyjnych autorskiego systemu ponadnormatywnych badań zużycia erozyjnego materiałów konstrukcyjnych i funkcjonalnych.

Introduction

Erosive wear refers to the mechanisms that affect the process of wear when striking erosive particles against the surface of mechanical elements [1]. More precisely, erosion is the process of the formation and accumulation of surface damage and the generation of mass losses due to the interaction of solid, liquid, or gaseous particles [2].

The main effects of erosion are damage to technical facilities, an impact on the effectiveness and safety of their use, and economic losses resulting from the need to replace or regenerate damaged elements and stop the technological process. The negative impact of erosion occurs especially in the following industries: aviation, energy, petrochemical, shipbuilding, and chemical [3, 4].

In the aviation industry, the erosion effect caused by rain, sand, volcanic ash and other particles acting in the air on airplanes is observed [5, 6]. The problem of erosion can have a major impact on the wear of parts and engine components, as well as aircraft shells [7]. Erosion has many negative consequences in the energy industry, especially in solid fuel fired power plants and in systems generating electricity from renewable energy sources, such as wind and water turbines [2]. Erosion and abrasive wear are important factors that generate costs related to transport, crushing, and delivery of powdered coal to boilers and the transport of ash after the combustion process [8].

The dynamic technological progress determines the increasing requirements with regard to newly designed machines and devices, which should be characterised by high reliability, functionality, and extended life in extreme environmental conditions. Those requirements increase expectations in relation to structural and functional materials, which should have very good mechanical properties, and resistance to high temperatures, friction, corrosion, and erosion

[9]. Traditional materials are replaced by lighter, more structurally complex compositions of materials that, at a lower mass, have the ability to carry higher loads [10]. The type of materials used is important, but the functionality of the material expected by the user is crucial.

A group of functional materials that are applied to engineering materials, in order to increase the operational durability, improve functionality, resistance to high temperatures, and limit corrosion processes and oxidation, include various types of coatings. The possibility of flexible shaping of coatings in the manufacturing process allows the achievement of the assumed functional properties [11, 12].

The use of modern construction and functional materials creates new application possibilities, but their effective application requires advanced research, including erosive wear testing. Physical phenomena and mechanisms occurring during erosion processes are an important but still poorly recognised factor that should be considered in the design of machinery and technical equipment. Therefore, new methods, methodologies, and procedures are being sought that will allow the study and identification of these phenomena.

Understanding the mechanisms occurring during erosive wear makes it possible to explain and define the initiation and the course of erosion wear processes, which are important for the durability, reliability, safety, and operation of machinery and equipment in many industries. The recognition of the erosion process also allows precise forecasting of the negative effects of erosion and the reduction of operating costs of machinery and equipment.

1. System for nonstandard testing

In order to predict erosive wear and effectively limit the negative effects of erosion, it is necessary to recognize the mechanisms and physical phenomena occurring during the erosion process. The course of the erosion process is difficult to mathematically model; therefore, an experimental study fulfils an important role in predicting the erosive wear of materials. Such tests allow precise selection of the material with the required erosion resistance for a particular application, depending on the parameters of the erosion process occurring in the target operating conditions. An effective method of reducing the negative impact of erosion is the use of advanced construction and functional materials that affect the increase of durability, reliability of machine parts and equipment, and the reduction of operating costs.

The analysis of the subject shows that there is a lack of a comprehensive erosive wear research methodology and a universal device that guarantees the implementation of erosion tests in a wide range of variability of the erosion process parameters. The developed erosive testing methodologies and available equipment are mainly designed for standard erosion tests or nonstandard tests, but dedicated only to specific applications.

The lack of research methodology that brings the possibility to perform comparative tests of various materials in a single research process and the lack of a device enabling the implementation of nonstandard tests has generated the need to develop a universal testing methodology as well as an original device ensuring the implementation of a wide range of erosion tests according to the developed methodology [13]. The developed methodology and test equipment form a system of nonstandard erosive wear tests (Fig. 1).

The erosive wear research according to the developed methodology was focused on determining the erosive resistance of materials and supporting the selection of materials for applications where there are erosive factors. The methodology allows the implementation of standard tests ensuring inter-laboratory verification of results and nonstandard operational tests simulating different erosion impact conditions in the target applications. The methodology also proposed several types of research, including accelerated research in the basic scope, which allow limiting the time and costs related to the implementation of erosive wear tests and extended research. The research methodology has been broadly characterised in the dissertation: "Methodology of erosive wear research of structural and functional materials" [13].

Precise investigations of the erosive wear process require research and test equipment that will allow for a wide range of adjustments of the test process parameters, especially regarding the velocity of the abrasive stream, dosing the erodent, and temperature changes. The analysis of the test equipment used in erosion tests showed the lack of a device that would ensure the implementation of research works according to the developed methodology. Due to the lack of advanced research equipment enabling flexible simulation of the erosion process, the Institute of Sustainable Technologies in Radom undertook the task of designing, manufacturing, and verifying the structure of the device for testing the erosion process. The device allows the simulation of the shock erosion process, during which the material is consumed as a result of the impact of the abrasive material transported in the compressed air stream. The main purpose of building an original research device was the possibility of carrying out nonstandard tests in a wide range of conditions, enabling the supply of information on the erosive wear of the tested materials to the developed information supply system, and then using the acquired knowledge in practical applications. It was assumed that the developed apparatus should allow for mapping the working conditions of various materials that occur

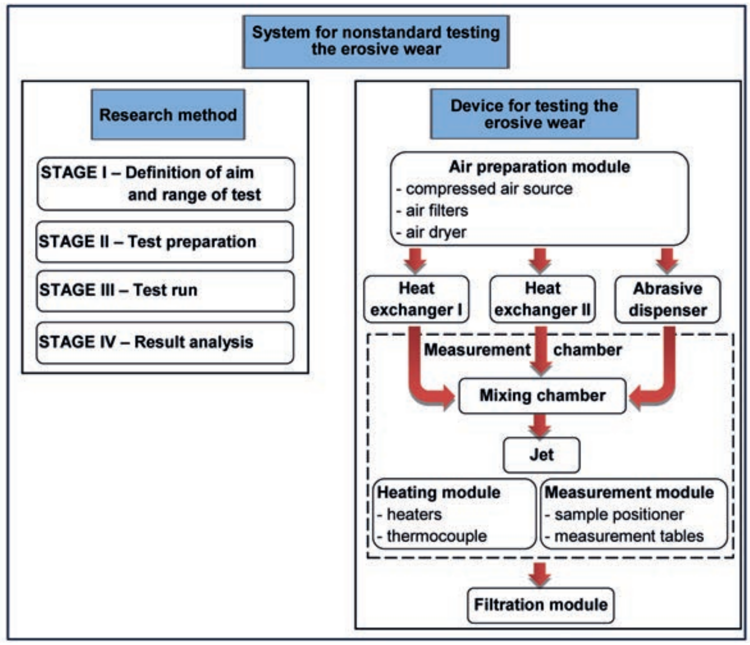

Fig. 1. Block diagram of a system of nonstandard erosive wear tests

in specific applications and the simulation of various extreme impacts with the possibility of modelling their intensity. It was also assumed that new material testing possibilities will be created as well as a method of the selection of the developed coatings for planned practical applications. However, the accumulated knowledge should allow the selection, design, and production of advanced functional and constructional materials as well as the verification of the effectiveness of the coating application technology.

2. The device for erosive wear testing

The designed device uses constructional solutions that have not been used in the erosive wear test equipment so far, e.g., independent temperature control of samples and the erosive mixture stream. Significant solutions have also been applied that have worked well in test equipment used to study erosion caused by aqueous media, but not used in systems with an air medium.

The device consists of an air preparation module, a dehumidifier, which is an important element of the pneumatic system, and a heat exchanger module enabling independent adjustment of the sample temperature and the temperature of the compressed air stream (Fig. 2).

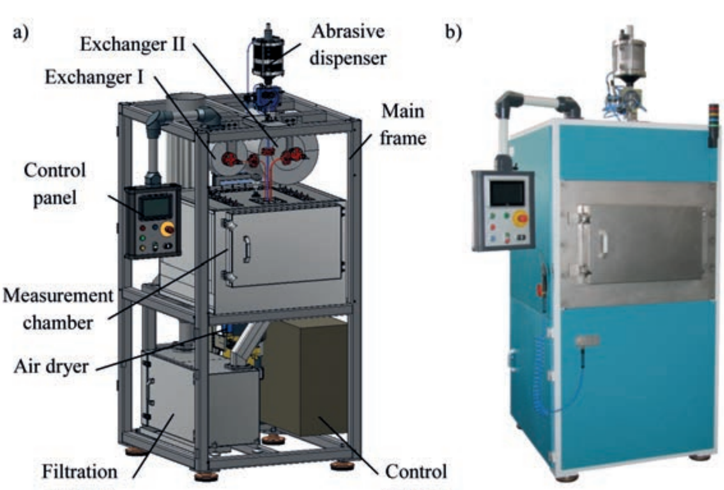

Fig. 2. Device for erosive wear testing: a) computer model – view without covers, b) picture of the developed device

The developed pneumatic system provides flexible control of the velocity of the mixture of compressed air and abrasive material in a wide range. In a single test cycle, it is possible to automatically change the velocity of the abrasive jet. The system controls the dew point and temperature of the air used to create the mixture with the abrasive material, which is extremely important for the precise and uniform process of dosing the erodent. The pneumatic system also provides a high class of purity of the air used during tests. The air filtration module and the dryer guarantee repeatability of air parameters during tests, regardless of the quality of air supplied to the device.

The main module of the device is the measurement chamber, in which the main parameters of the erosive wear process are shaped, including abrasive and air mixture, sample temperature, and the angle of attack of the abrasive stream. In the chamber, there is a sample positioner equipped with a set of measurement tables and a set of heaters allowing the samples to be heated up to a given temperature.

The positioner is placed centrally in the axis of the chamber (Fig. 3). In an automatic cycle of tests on several samples, the craters are made one after the other on samples from 1 to 8, while the positioner rotates every 45°, after changing the position the nozzle axis coincides with the sample axis. In manual test mode, the sample eroding sequence is arbitrary. An important advantage is the ability to precisely control the change of the angular position of the positioner by a given value. The developed solution allows one to make several erosional craters on the sample. This applies, in particular, to samples coated with hard coatings, because the craters then have a maximum diameter of a few millimetres. The positioner ensures that eight samples from different materials are installed in the measuring chamber. Each sample can be inclined at a different angle in relation to the axis of the stream of abrasive material eroding the tested material.

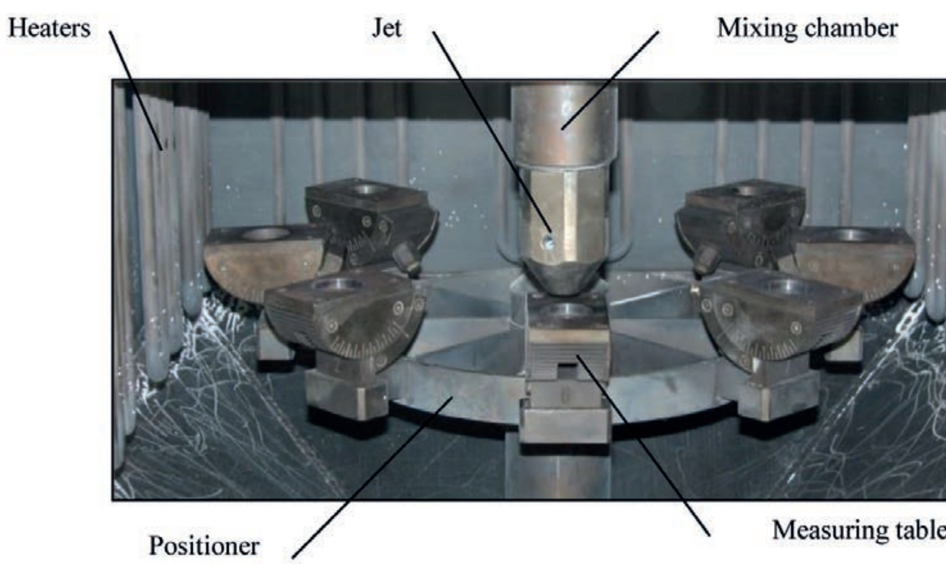

Fig. 3. The interior of the measurement chamber

An important function of the device is the ability to perform tests at room temperature and in high temperatures up to 600°C, with the maximum velocity of the stream of abrasive mixture flowing out of the nozzle of 130 m/s. The introduction of two independent heating modules allows the implementation of high-temperature tests in three variants. In the first one, only the sample is heated, while the air stream and the abrasive remain cool. In the second version, the stream of the mixture is heated while the sample is cool. In the third variant, both the sample and the mixture of air and abrasive material are heated. The proposed variants of high-temperature tests are an important advantage of the device for simulating the process of erosive wear.

An abrasive material dispenser was also used to ensure smooth and precise dosing of various abrasive materials. Available equipment used in erosion tests is calibrated for one type of abrasive material. The developed device was calibrated basically for erosion tests using aluminium oxide. The functionality of the designed abrasive dosing module also allows the implementation of tests using various erodents.

After changing the abrasive material, the flow rate and velocity of the abrasive stream should be verified, because these parameters affect the intensity of erosive wear. In order to calibrate the device, a calibration module was used, which was used to measure the velocity of the abrasive stream with the double-disc method and the erodent flow rate control module. The use of calibration modules significantly extends the possibility of performing nonstandard tests using various abrasives. Information collected during the calibration of the device using various abrasive materials is used to build the knowledge base.

The device developed is a functional tool for researchers investigating the erosion resistance of materials. The possibility of precise control of a group of erosion process parameters allows simulation of different impact conditions of impact erosion. In particular, it gives the possibility of mapping the natural operating conditions of machine parts and devices appearing in the targeted applications exposed to the impact of erosion processes. The device's functionality provides many research possibilities, including the recognition of the mechanisms of wear and the identification of the methods of limiting the process of erosion of mechanical elements from many industries, including energy, petrochemical, aerospace, and automotive industries.

3. Verification of the developed system

The verification tests included developed technical solutions, i.e. original effector modules and an integrated erosive wear testing device. The ranges of parameters of the erosion process that can be simulated on the developed device were determined. The purpose of the verification tests was also to determine whether the designed device brings the possibility of simulating different conditions for the exploitation of materials in a single test cycle. It was checked whether the system allows providing information on the erosive resistance of materials and physical phenomena occurring during the erosion process, which are important during the development of new materials with increased erosive resistance. The possibility of conducting comparative tests of construction and functional materials in a single test cycle was also verified, and it was checked whether the calibration procedures developed allowed for the calibration of the device for erosive wear testing within the assumed erosive stream velocities and abrasive volume. Therefore, the verification did not concern conducting material cognitive tests, but demonstrating the possibility of carrying out such comprehensive studies of the erosive wear of structural and functional materials using the developed system.

As part of the verification of the device for testing erosive wear, it was found that the developed effector modules guarantee the simulation of the erosion process in the assumed parameter ranges. The developed pneumatic module brings the possibility of controlling the velocity of the erosive stream in the assumed range of 30–130 m/s (Fig. 4).

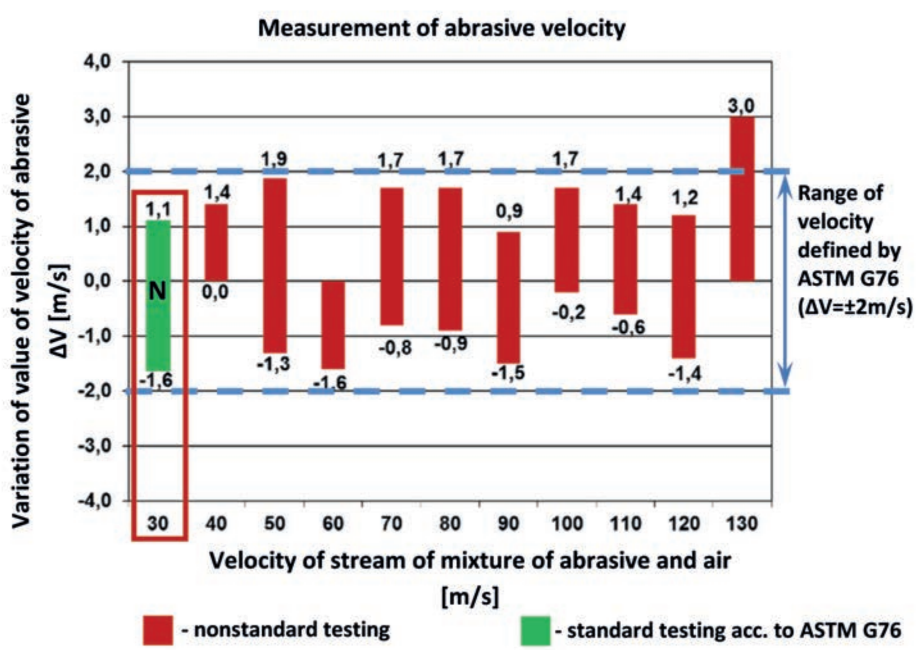

Fig. 4. Graph of the change of the abrasive stream velocity in the range 30–130 m/s, determined by the double-disc method

Obtained results of the verification of the pneumatic module showed that the implementation of nonstandard tests with the deviation required in the standard (±2 m/s) is possible in the range of erosive stream velocity of 30–110 m/s.

The dispenser design ensures a supply of abrasive materials with a maximum deviation of ±0.3 g/min in the entire range of the abrasive stream velocity of 30––130 m/s, which is smaller than the standard requirements (Fig. 5).

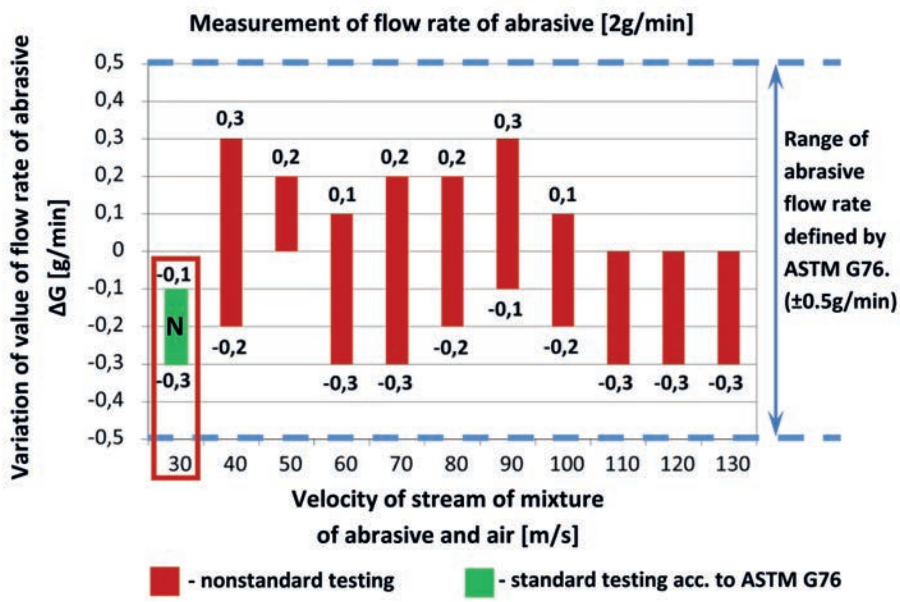

Fig. 5. Graph of the measured accuracy of the abrasive material flow rate for the value of 2 g/min

Verification of the effector modules of the erosive wear test device showed that the developed system allows the implementation of standard tests as well as a wide range of nonstandard tests. It also allows tests at increased temperatures up to 600°C, with the possibility of independent control of the sample temperature and the temperature of erosive mixture stream (Fig. 6).

Due to the wide range of erosive wear tests that the developed system provides, comparative testing of materials has been carried out in the nonstandard test type in the basic range, which is carried out only at room temperature. In the selected type of tests, the basic parameters, i.e. abrasive material, abrasive flow rate, temperature, and test time, are defined in the ASTM G76 standard. During tests, the values of parameters specified in the standard were unchanged. However, the value of the angle and velocity of the erosive stream was selected individually. In order to confirm the possibility of comparative tests at increased temperatures and to demonstrate physical phenomena occurring at high temperatures, the scope of basic research was extended to include erosive tests at temperatures up to 600°C.

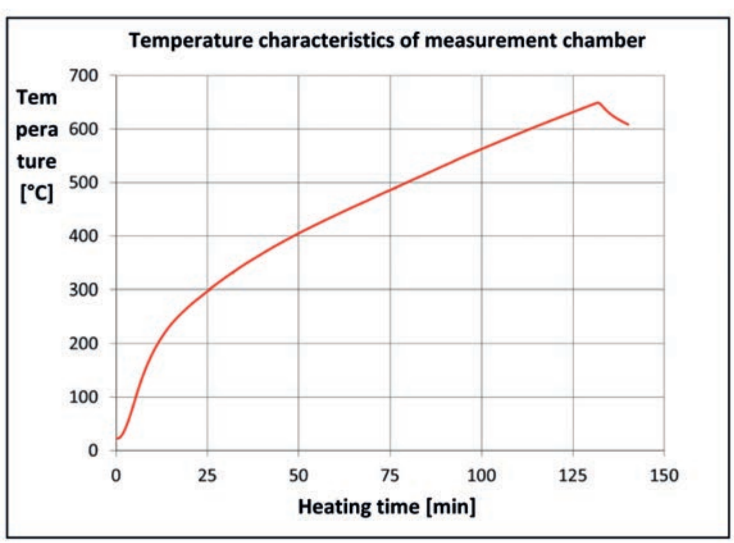

Fig. 6. The temperature characteristic of the measurement chamber

The sample results of the erosive wear tests of Ti6Al4V construction material and the TiZrN functional coating for the erosion rate of 30 m/s, 50 m/s, and 70 m/s, and the angle of attack of 50° are shown in Fig. 7.

Analysis of the surface geometry of Ti6Al4V construction material samples showed that, in the range of standard parameters according to ASTM G76, erosive wear was not present. Moreover, in the area of nonstandard tests in the range of 30–50 m/s of stream velocity and 50–90° of angle of attack, the analysis showed no erosive craters, while the increase in the volume of material above the upper surface of the sample was observed in the area of the impact of erosive stream. The erosive craters occurred with the increase of the erosive stream velocity above 50 m/s, especially for the 50° angle of attack. During the impact of the erosive stream at an angle of 90°, craters occurred only at the velocity of the erosive stream of 90 m/s. In order to explain the increase in the volume of the sample, the surface geometry and chemical composition of the outer layer of the eroded sample and the micrograph of erosive particles were analysed. During the eroding process, accelerated particles of abrasive material dug into the material being tested. Then, consecutive grains in the form of a conglomerate as a result of collision with the tested material dispersed into smaller ones, connected with the substrate, creating a crust on the surface of the sample. Instead of the crater and the volume loss of the material, an increase in the sample volume was observed.

The erosion tests of titanium alloy coated with TiZrN coating were carried out in identical conditions as the testing of the construction materials. To demonstrate the effect of a single parameter of the erosion process on the intensity of wear, it was assumed that the TiZrN coating tests carried out at room temperature were performed until the coating was penetrated to the substrate material. At that point, the coating loses its anti-wear properties, and further testing for determining the erosion resistance is unjustified.

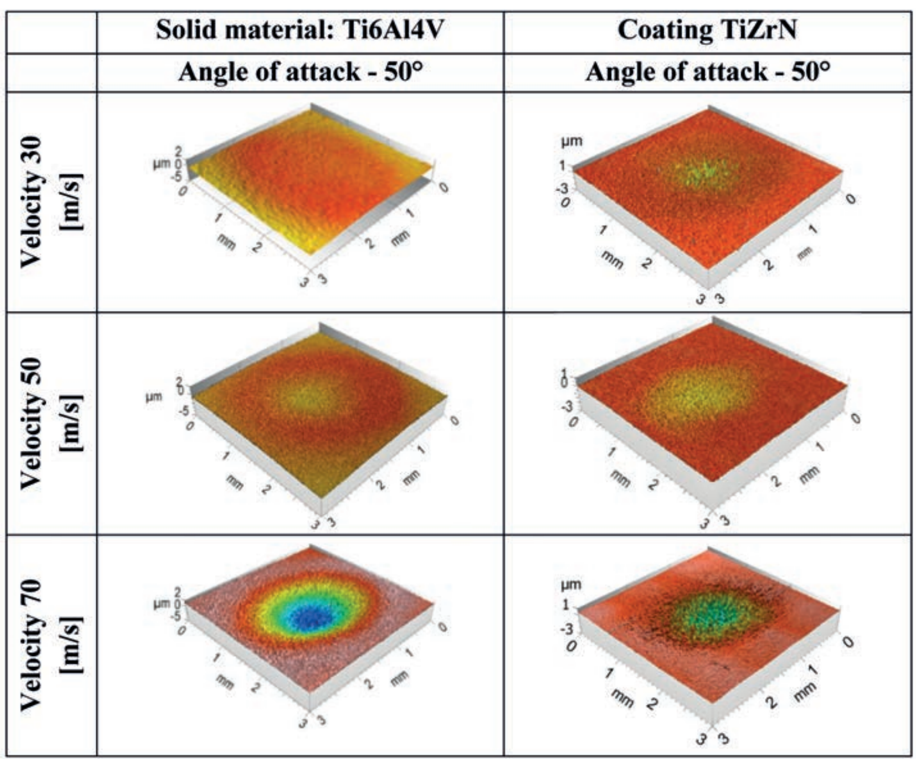

Fig. 7. Scans of geometry of material Ti6Al4V and TiZrN for the attack angle of abrasive stream 50°

Analysing the intensity of erosive wear in the range of erosion stream velocities of 30–50 m/s, the coating was not damaged. There was also no observed phenomenon of deposition of abrasive material on the surface of the sample, which occurred in the case of construction materials. During erosion tests at the 90° attack angle and the erosive mixture velocity of 50 m/s, the first signs of erosive wear were observed. As the velocity increased above 50 m/s, an increase in erosive wear was observed. During the tests carried out at the erosive stream velocity of 60 m/s, the maximum depth of the craters was 2.8 μm. With the increase of the velocity to 70 m/s, the coating was penetrated to the substrate material. The erosion craters made on samples of Ti6Al4V materials had a larger diameter compared to the craters formed on the TiZrN coating.

Whether the phenomenon of erodent settling occurs during tests at increased temperatures was also verified. As the functional coating used for testing at 600°C became plasticised and then separated from the base material, the results of comparative testing of construction and functional materials were presented at 300°C, in which the coating retained its functional properties. Analysis of the surface topography of the samples showed that, regardless of the type of material tested, there was a phenomenon of abrasive deposition on the eroded surface (Fig. 8). Determination of the volume of material removed was impossible, because the abrasive filled the erosion crater. This was also the situation in the range of parameters in which this phenomenon did not occur in studies at 25°C.

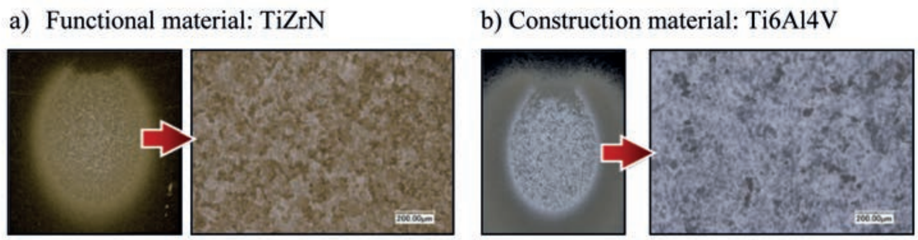

Fig. 8. Micrograph of erosion craters covered with a layer of abrasive material during tests at 300°C, attack angle of 50°, velocity of erosive stream 90 m/s: a) TiZrN coating, b) titanium alloy Ti6Al4V

Conclusion

The developed system (device and research methodology) is an important tool for researchers investigating the erosion resistance of materials. The possibility of precise control of the parameters of the erosion process allows the simulation of different conditions of effects of impact erosion. In particular, it gives the possibility of mapping the natural operating conditions of machine parts and devices appearing in the targeted applications exposed to the effects of erosion processes. The results of erosive tests allow the selection of materials for the targeted technical solution, guaranteeing erosive resistance in conditions occurring in the operating environment. It is also possible to determine the boundary parameters of the erosion process, beyond which there will be an increase in the intensity of material consumption. The device's functionality provides many research possibilities, including recognising the mechanisms of wear and identifying the possibilities of limiting the process of the erosion of machine elements and technical devices.

An important advantage of the system is the integration of erosive wear tests, including standard tests, nonstandard operation tests, model tests, and increased temperature tests. The device brings the possibility of performing comparative tests of various materials in a single test cycle, with the possibility of placing up to eight samples in the measurement chamber and independent control of the angle of inclination of the sample relative to the erosive stream. The developed device also provides tests at elevated temperatures up to 600°C with the possibility of independent temperature control of the sample and erosive stream. The verification tests confirmed the universality of the device and the possibility of performing nonstandard tests of construction and functional materials in a widely variable range of erosion process parameters.

The developed erosive wear testing system ensures the implementation of tests in accordance with applicable standards and a wide range of nonstandard tests for engineers designing elements of machines, devices, and pneumatic transport installations exposed to erosive factors, as well as technologists involved in the application of new construction and functional materials with increased erosion resistance and researchers dealing with the development of novel material solutions for construction and functional materials as well as scientists studying physical mechanisms and phenomena occurring during the impact erosion process.

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