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SUBSTANTIATION OF THE CHOICE OF METHODS OF NON-DESTRUCTIVE TESTING OF ELEMENTS OF ENERGY EQUIPMENT USING A FUZZY LOGIC APPARATUS

Abstract. The paper illustrates the solution of the problem of choosing methods of quality control of manufacturing parts and assemblies of power equipment using a fuzzy logic device. The main methods of non-destructive testing for the detection of surface and internal defects are considered, as well as the main indicators of quality of metal products. The types of metal defects and welded joints are inspected. The description of the equipment and means of control for detection of defects is executed. The sequence and methods of quality control by ultrasonic, capillary and magnetic powder methods of control are described in detail. The results of quality control of parts during production and during their operation are obtained. The analysis of the revealed defects is carried out. An example of using an integrated approach to control is given. The obtained results of control of the percentage of coincidence of detection of defects on the product are analyzed. Comprehensive quality control was performed by visual, ultrasonic, capillary and magnetic powder methods of non-destructive testing to determine the percentage of coincidences of defects. By creating a heuristic analyzer based on the interface of the fuzzy logic system Fuzzy Logic Toolbox of the Matlab program, an example of determining a combination of non-destructive testing methods for quality control of a steam turbine bearing liner is considered. Computer simulation according to the Mamdani algorithm is carried out, which consists of fazzification with determination of ranges of change of input values for each example, task of distribution functions for each input parameter; calculation of rules based on the adequacy of the model; defuzzification with the transition from linguistic terms to quantitative assessment and graphical construction of the response surface. The simulation made it possible to determine the optimal combination of non-destructive testing methods, which provides the highest quality of defect detection in the steam turbine bearing liner.

Keywords: control object; defect; non-destructive testing; fuzzy logic; heuristic analyzer; fuzzification; defuzzification; quality control.

Introduction

The development of modern energy, machine-building and metallurgical production is inextricably linked with the creation and improvement of methods and means of non-destructive testing (NDT), allowing to ensure high reliability and safety. Improving the quality and reliability of industrial products is possible under the condition of continuous improvement of production technology and continuous quality control of products. Control of product parameters in the industry is characterized by sufficient complexity and high cost, so the task of introducing mass control of product parameters without increasing their cost is timely and relevant. To assess the technical condition of critical facilities and units of power equipment at various stages of production and operation in many industries, the methods of NDT are widely used. Among a large number of methods and means of NDT objects and units of power equipment, a special place is occupied by ultrasonic, color (luminescent) and magnetic powder methods.

For the implementation of modern flaw detection use a wide range of serial devices and non-destructive testing, but in each case, there is a specificity (structure and properties of the object of control, its shape and design, etc.), which necessitates additional research and development of specialized controls. This is especially evident during flaw detection of products with a complex surface. An important problem is the display of the shape and size of the detected defects in the products, which are both in operation and during their manufacture.

Very often the use of one control method is not enough to check the quality of the product in accordance with the technical documentation for the product. In such cases, a set of NDT methods is used. In some cases, in practice, there may be problems for which the use of known methods (or techniques) of NDT is not effective. In these cases, research institutes and plants are developing new special methods, tools and techniques of non-destructive testing. Therefore, the substantiation of the use of the necessary methods of NDT and the means that implement and ensure the identification and determination of the characteristics of defects of parts and components of power equipment, is an urgent scientific and practical task.

Analysis of basic research and publications. One of the main priorities in the production of most products is the quality of the final product. The struggle to improve the quality of manufactured products is synonymous with the struggle for the consumer in a free market [1 – 5]. This statement is especially important in the manufacture and operation of critical products and structures. Obviously, a defective unit used in a particular mechanism or structure is much less, and failure in the best case will cause the mechanism to stop, at worst – can lead to disaster. Thus, quality control is a prerequisite for metal products, which are components and parts of the responsible objects.

For qualitative assessment of such objects, the methods of NDT are widely used [1, 2].

According to the current standard [4 – 5] in non-destructive testing it is accepted to classify 9 types of NDT, which unite on the basis of the used physical phenomena and the nature of probing fields.

It is necessary to allocate the most widespread in technique methods of NDT for the comparative analysis and revealing of their advantages and lacks for the decision of problems of flaw detection.

Objects of control differ in a wide variety of forms, properties of materials, and also the list of defects characteristic of them. This necessitates the analysis of the main problems in the control of various methods. This is especially true of metal products, which occupy a leading position in terms of output. One of the main indicators of the quality of metal objects is the presence of defects.

Defects can impair physical and mechanical properties of metals, such as strength, ductility, density, electrical conductivity, magnetic permeability, etc. They are often divided into overt and covert. The first is detected by a visual method of control or by means of tools and methods that are given in the regulatory documentation. If the defects are most likely detected by appropriate instrumental methods of NDT, but are not detected visually, they are also classified as obvious. The latent defect cannot be detected by the intended method and equipment. Defects are also divided into critical, the presence of which makes the use of products for their intended purpose impossible or dangerous; significant – significantly affect the performance of the product or its durability; insignificant, which do not have such an impact, as well as insurmountable and surmountable.

By origin, defects are divided into production-technological and operational. The first include metallurgical defects that occur during casting and rolling; technological, arising during the manufacture of products and their repair, and before the operational – defects that occur after some operation of the products due to fatigue of the metal, their elements, corrosion, wear, as well as improper maintenance and operation.

According to the number and nature of distribution in the products, the defects can also be single, local (cracks, shells, etc.), distributed in limited areas, such as areas of corrosion, distributed throughout the product, for example, the heterogeneity of chemical composition; external (surface and subsurface) and internal (deep).

By the nature of geometric parameters, defects can be point, linear, planar and three-dimensional.

Depending on the size of metal defects are divided into sub microdefects, microdefects and macro defects.

Macro defects can be small or large. Usually, for the classification and identification of macro defects, their morphological and genetic characteristics are used.

Analysis of works [1 – 3] shows that the most common and dangerous defects are cracks of different origin. Under the influence of residual and operating stresses, cracks can propagate at high speeds. Therefore, the micro- destruction caused by them often occurs almost instantly and poses a high risk. Moreover, in comparison with extended cracks of all kinds, round defects are less dangerous and more static in their development.

Thus, the assessment of the nature of the defect (whether it is long or rounded) is important information in diagnosing and predicting the residual life of the test object.

The aim of the study. When choosing a method or a set of NDT methods for specific parts or assemblies, it is necessary to take into account the following main factors: the nature (type) of the defect and its location, the sensitivity of the control method, the working conditions of the parts and technical specifications for the product, the part material, the condition and roughness of the surface, the shape and size of the part , condition and roughness of the surface, shape and size of the part, control zones, accessibility of the part and the control zone, control conditions [1 – 3].

The study used three main methods of non-destructive testing that are used at enterprises and plants in the manufacture of parts and assemblies of power equipment, namely: capillary (color flaw detection), magnetic particle and ultrasonic testing. They were not chosen in vain, since they have a number of advantages and features in use (ease of control, speed, sensitivity, information content). It is the integrated control that makes it possible to assess the quality of the product as a whole.

Main part

Ultrasonic Testing method of product quality control. Let us consider ultrasonic testing using the example of welded joints of the rotor frame of the SGK 538 / 160-70UHL4 hydrogenator, which was operated at one of the Ukrainian hydroelectric power plants (Fig. 1). The method of control and adjustment of the flaw detector was carried out according to DSTU, drawings and other normative and technical documentation. To complete the task, the surface of the test object was prepared in accordance with the methodological instructions, in our case it is a fragment of the butt welded joint of the hydrogenator rotor rim discs to each other (Fig. 2) and setting up the flaw detector for operation**.**

Fig. 1. The skeleton of the rotor of the hydrogenator

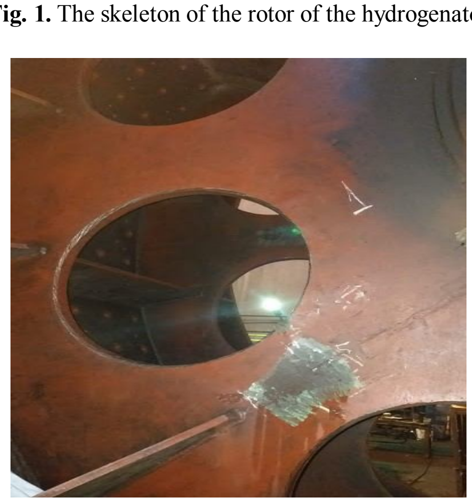


Fig. 2. Fragment of the butt welded joint of the rotor rim disks

The control was carried out with a UD4-TM flaw detector and a SWB 45-2 converter, which was initially set up according to the control method on a standard sample V2 (setting the depth gauge, vibration velocity in the material and other auxiliary values of the transducer) and built an electronic ADD diagram (amplitude-distance-defect) for a fixation level of a defect equal to 2 mm. Next, we gradually move on to control. During the inspection, it was revealed that on the fragment of the butt welded joint, which had to be inspected, with the section length L = 400 mm, single load-bearing integrity was revealed that did not exceed the fixation level, as well as lack of penetration of the root of the seam, which is unacceptable for all types of welded joints.

The results obtained indicate that the detected lack of penetration must be corrected. Modern standards for assessing the quality of products do not allow the use of products with these types of defects.

Penetrant Testing method of product quality control. Let us consider the Penetrant Testing method (color defectoscopy) using the example of the bearing shell of a steam turbine bearing (Fig. 3), which are intended for operation at a thermal power plant in Ukraine.

Fig. 3. Steam turbine bearing insertion

Fulfillment of the task for carrying out the Penetrant Testing method (color defectoscopy) on the example of the bearing shell of a steam turbine bearing. Surface preparation was carried out according to the guidelines. The ambient temperature was + 14 ° C, which is favorable for the control. During the control, aerosol cans were used, namely: penetrant – MR68C, cleaner – MR70, developer – MR88. The lighting in the room was combined. The task was to carry out a color defectoscopy of the fit of the babbitt fill to the steel base of the insert.

During defectoscopy, the part was cleaned of dirt and dust and a penetrant was applied. After 5 minutes of exposure, the penetrant was reapplied to improve the permeability of the active substance. After 15 minutes of exposure, the part was cleaned according to the control procedure and the developer was applied. After the developer had dried, linear indications were found on the verge of babbitt pouring and the steel base of the steam turbine bearing shell**.** Linear indication detected is unacceptable when babbitt casting is in contact with steel base. This indicates that mistakes were made in the technological process, in the manufacture of the product. In order to accept this part into work, it must be corrected by re-pouring and checking. Modern standards for assessing the quality of products do not allow the use of products with these types of defects. This type of defect can lead to an accident during the operation of the product.

Magnetic particle Testing method of product quality control. Let us consider the Magnetic particle Testing method using the example of a workpiece (forging) for the manufacture of tie rods with M160 thread. Testing methods and flaw detection materials according to GOST, drawings and other normative and technical documentation.

To complete the task, the surface of the test object was prepared, in our case it is a blank (forging) for the manufacture of tie rods with M160 thread. After cleaning the surface, a 20 μm layer of contrasting white paint is applied to it, as the magnetic suspension in black MR76S will be used. In our case, we use a magnetizing device (yoke) AC-42 V, operating on alternating current using the applied field method. The magnetic field strength on the controlled area of the object surface is H = 2.2 kA / m. We slowly magnetize the workpiece and apply a magnetic suspension. After holding on the surface of the test object, a linear indication with a length of L = 42 mm appeared, which is located at the point of thread cutting.

Having analyzed the width of the display opening and its length, one can declare the inadmissibility of defects of this type. The blank is not suitable for further stud production. This type of defect can lead to an accident during the operation of the product.

Comprehensive non-destructive testing of products quality control. On the above-described products of units and parts of power equipment, a comprehensive quality control was carried out by the following main NDT methods, such as visual, ultrasonic, magnetic particle and penetrant testing, which made it possible to determine the percentage of coincidences in the detection of defects, the results of which are shown in Table 1.

After analyzing the results obtained, we can conclude that it is necessary to use comprehensive quality control of products, since it is impossible to highlight the importance of one of the main methods. Only an integrated approach makes it possible to judge the presence and nature of the identified defects, taking into account all the advantages and features of using NDT methods. Using the example of a common test object (a bearing shell of a steam turbine bearing), we will consider the expediency of using a complex NDT.

Assessment of the quality of control using a fuzzy logic apparatus. In practice, when evaluating metal products by NDT methods and tools, it becomes necessary to find a balance between the reliability of the results and the cost of testing. The economic feasibility of NDT is one of the main indicators of competitiveness in the market for such control services. So, there is a need to determine a combination of such NDT methods, allowing to obtain the greatest reliability of control results while minimizing the cost of its implementation.

Table 1 – **The percentage of coincidences in the detection of defects**

Product name	NDT methods				Percentage of coincidences in detecting defects, %
	Visual Testing	Ultrasonic Testing	Magnetic particle Testing	Penetrant Testing	
Fragment of the butt-welded section of the rotor rim disks	-	+	-	-	25
Steam turbine bearing support shell	+	+	+	+	100
Tie rod (workpiece)	-	-	+	+	50

The solution to this problem is possible due to the use of a fuzzy logic apparatus, is widely used in solving control problems, evaluations in decision-making systems under fuzzy, blurry conditions. The subject of fuzzy logic is the study of judgments in conditions of fuzzy. Calculations and construction of fuzzy logic diagrams can be performed using the MatLab computer program in the fuzzy logic application.

Let us consider using an example of determining a combination of NDT methods for quality control of a steam turbine bearing support shell, how a fuzzy logic system works.

Quality control of the manufacturing of the steam turbine bearing support shell can be carried out using the radiation monitoring method.

This control method gives the most reliable results (in this case) and can be taken as exemplary (100% quality).

However, this method is the most expensive and most dangerous compared to other methods. Not every enterprise has the ability to use radiation monitoring due to its complexity, danger, and the need for qualified specialists. In such cases, production workers are trying to replace radiation control with other methods. No doubt, the combined control gives the most reliable results, but how to determine the appropriate combination of methods to use?

Currently, there are many fuzzy logic algorithms. Most often everyone uses the following methods: Mamdani, Tsukamoto, Sugeno, Larsen. The main analytical relations describing the functioning of the Mamdani algorithm, presented in [6]. In works [7 – 9] the possibilities of using the Mamdani algorithm are presented. The paper [10] presents a solution to the problem of classifying defects in metal pipes of oil and gas pipelines using the Mamdani fuzzy inference algorithm and the Sugeno fuzzy knowledge base. In [11], a method was proposed to improve the accuracy of detecting defects in metal products, the possibility of using the apparatus of the theory of fuzzy sets to determine such parameters of the transducer that would give the opportunity to minimize the error in determining a defect was proved. In [12], the solution to the problem of controlling the accuracy of the parameters of the technological process of producing kefir and improving its quality by creating a heuristic analyzer is considered.

To build a heuristic analyzer, we first use the Mamdani fuzzy inference algorithm. Since the enterprise considers the possibility of using three control methods (visual control is input and is not taken into account), the model should have three inputs and one output. Select the Penetrant Testing (PT) as the first input.

The second input is the Ultrasonic Testing (UT). The third entry is the Magnetic Particle Testing (MT). We select the quality of control (Quality) as the initial value (Fig. 4).

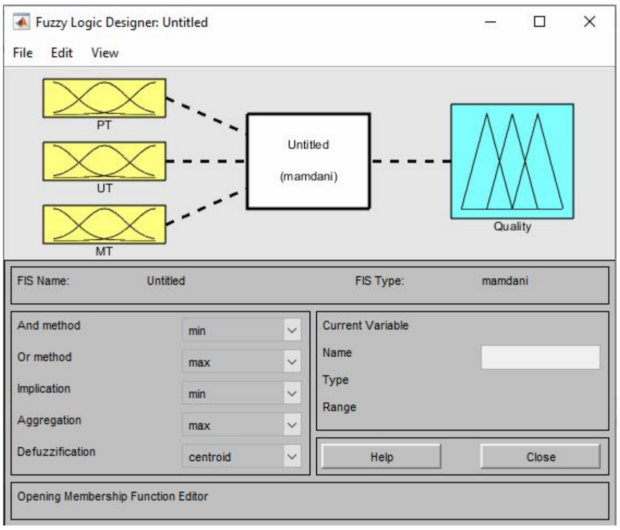


Fig. 4. Window of the task of input and output parameters when monitoring the quality of the state of the bearing shell of a steam turbine bearing

We define membership functions for the selected input variable – the Penetrant Testing (PT). In the Range item, set the range in which the function changes (from 10% to 40%) of defects. We set the type of the membership function in the Type column: for three membership functions, namely the minimum (min), average (middle) and maximum (max), we choose the Gaussian distribution.

Similarly, we set the membership functions for the selected input variable – the Ultrasonic Testing (UT). In the Range item, set the range in which the function changes (from 25% to 80%).

We set membership functions for the selected input variable – the Magnetic Particle Testing (MT). In the Range item, set the range in which the function changes (from 35% to 70%).

We set membership functions for the selected initial variable – quality control. In the Range item, set the range in which the function changes (from 0% to

100%). We set the type of the membership function in the Type column: for three membership functions, namely the minimum quality, average quality and high quality, we choose the distribution (trimf) a triangular distribution law. We set the rules according to which the model will operate. The rules are based on the model:

the rule 1: $IF\ [x \in A_1]\ AND\ [y \in B_1]\ TO\ [z \in C_1];$

the rule 2: $IF\ [x \in A_2]\ AND\ [y \in B_2]\ TO\ [z \in C_2];$

the rule 3: $IF\ [x \in A_3]\ AND\ [y \in B_3]\ TO\ [z \in C_3],$

where $x, y, z \ldots$ – nominal output (input) linguistic variables, $A_1, A_2, A_3, B_1, B_2, B_3, C_1, C_2, C_3 \ldots$ – are some fuzzy sets, described by their membership functions.

In the "rules" window, we will compose rules that characterize how the quality of control changes depending on the selected combination of control methods (Fig. 5).

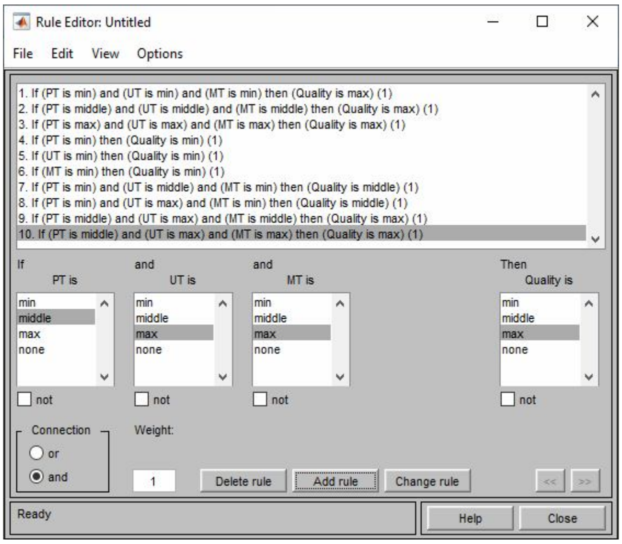


Fig. 5. Window for setting rules

In Fig. 6. the windows of the values of the variables are presented:

a – at 50% compliance with the input parameters;

b – at 100% compliance with the input parameters.

The response surfaces for a combination of control methods are shown in Fig. 7.

Conclusions

1. The study examined three main methods of non-destructive testing quality of power equipment products: ultrasonic, capillary and magnetic particle NDT methods.

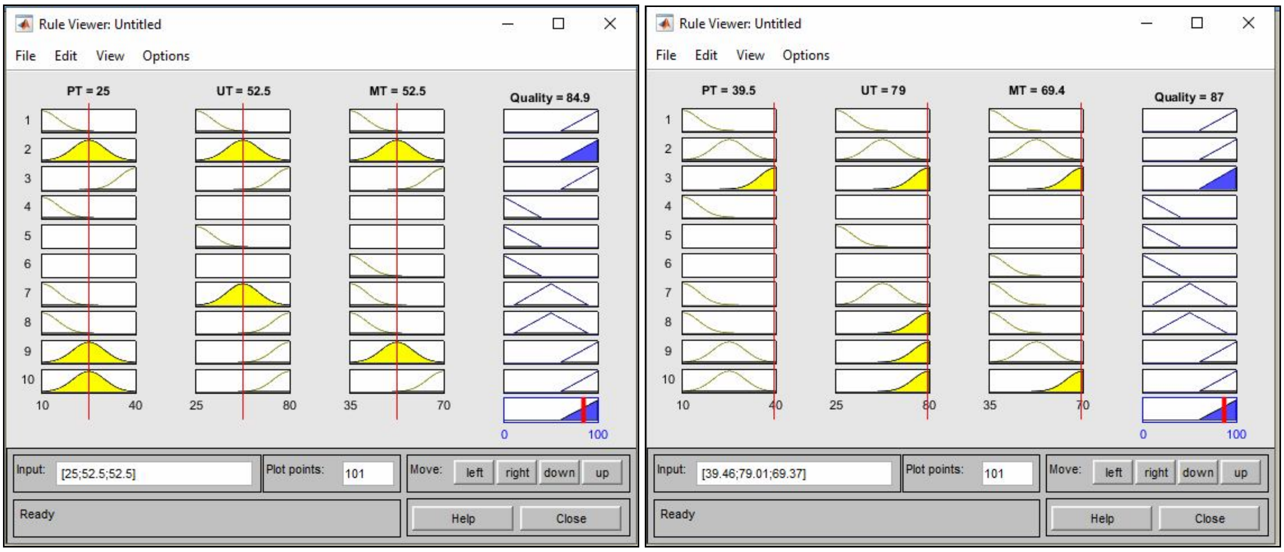
The results of quality control of parts at various stages of production and operation are analyzed in detail, as well as a reasonably comprehensive approach to performing non-destructive testing.

The revealed defects only indicate the need to implement the use of a complex of NDT methods at all stages of production and operation of products. This can save not only the funds of enterprises, but also human lives.

2. By means of the graphical user interface, it was possible to build a fuzzy logic system that solves the problem of finding the necessary combination of NDT methods to ensure high quality control of used products.

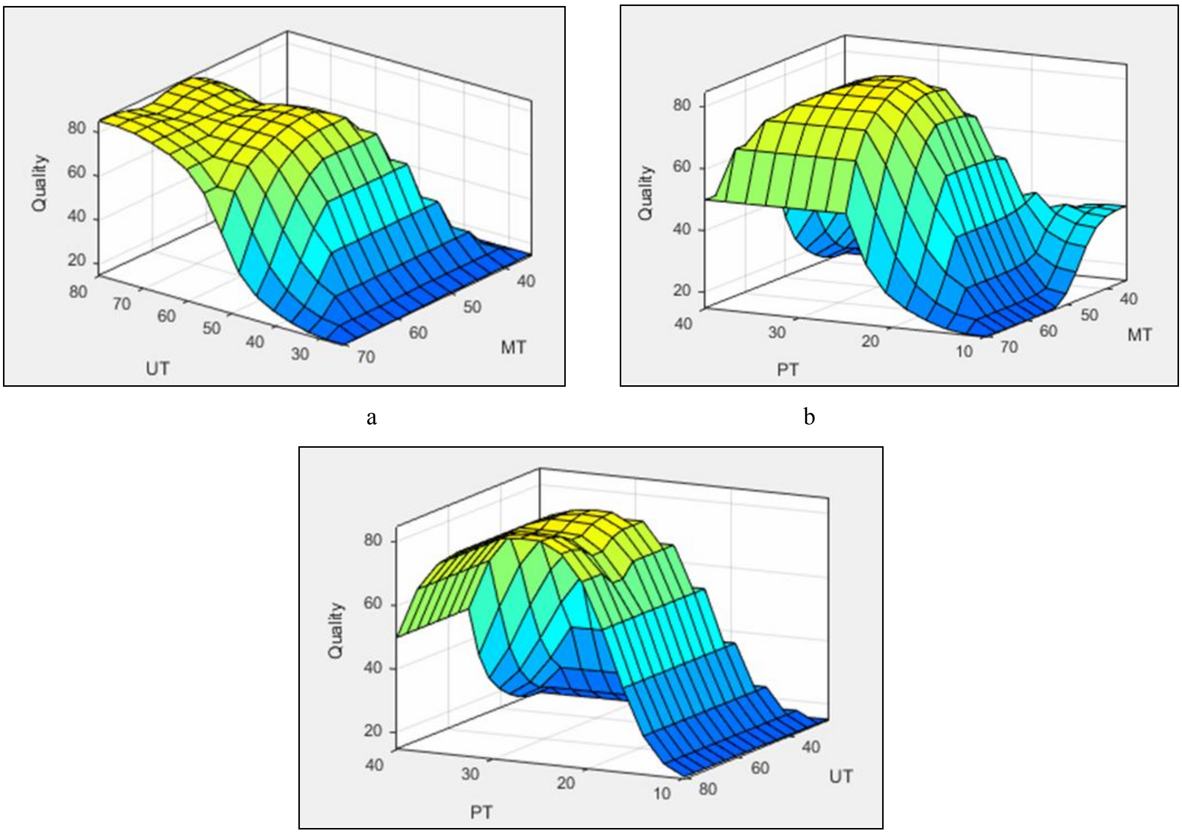
3. The proposed heuristic analyzer plays the role of an advisor for the defectoscopist- engineer in choosing the necessary combination of methods for carrying out a comprehensive non-destructive quality control of products.

4. From the obtained results of computer simulation, the following conclusion can be drawn: when monitoring the quality of the state of the bearing shell of a steam turbine bearing, it is advisable to use a combination of two methods of non-destructive testing (ultrasonic and magnetic particle), because they give the maximum quality of control at the level of 87%.



a b

Fig. 6. Window of variable values window:
a – at 50% compliance with the input parameters;
b – at 100% compliance with the input parameters



a b

c

Fig. 7. Window of variable values window:
a – the dependence of the quality of control with the combined use of the ultrasonic method and magnetic particle;
b – the dependence of the quality of control with the combined use of the capillary method and magnetic particle;
c – the dependence of the quality of control with the combined use of the capillary method of ultrasonic

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Обгрунтування вибору методів неруйнівного контролю елементів енергетичного обладнання за допомогою апарату нечіткої логіки

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Анотація. В роботі проілюстровано рішення задачі вибору методів контролю якості виготовлення деталей та вузлів енергетичного обладнання за допомогою апарату нечіткої логіки. Розглянуто основні методи неруйнівного контролю для виявлення поверхневих та внутрішніх дефектів, а також висвітлено основні показники якості металовиробів. Проведено огляд видів дефектів металу та зварних з'єднань. Виконано опис обладнання та засобів контролю для виявлення дефектів. Детально описано послідовність та методика контролю якості ультразвуковим, капілярним та магнітопорошковим методами контролю. Отримано результати контролю якості деталей при виробництві та в процесі їх експлуатації. Проведено аналіз виявлених дефектів. Приведено приклад використання комплексного підходу до виконання контролю. Проаналізовано отримані результати контролю відсотку збігу виявлення дефектів на виробі. Проведено комплексний контроль якості візуальним, ультразвуковим, капілярним та магнітопорошковим методами неруйнівного контролю для визначення відсотку збігів виявлення дефектів. За допомогою створення евристичного аналізатора на базі інтерфейсу системи нечіткої логіки Fuzzy Logic Toolbox програми Matlab розглянуто приклад визначення комбінації методів неруйнівного контролю для контролю якості вкладишу підшипника парової турбіни. Проведено комп'ютерне моделювання за алгоритмом Mamdani, який складається з фазифікації з визначенням діапазонів зміни вхідних величин для кожного прикладу, завданням функцій розподілу для кожного вхідного параметра; обчислення правил, виходячи з адекватності моделі; дефазифікації з переходом від лінгвістичних термів до кількісної оцінки та графічної побудови поверхні відгуку. Моделювання дало змогу визначити оптимальну комбінацію методів неруйнівного контролю, що забезпечує найвищу якість виявлення дефектів у вкладишу підшипника парової турбіни.

Ключові слова: об'єкт контролю; дефект; неруйнівний контроль; нечітка логіка; евристичний аналізатор; фазифікація; дефазифікаціяж контроль якості.

Обоснование выбора методов неразрушающего контроля элементов энергетического оборудования с помощью аппарата нечеткой логики

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Аннотация. В работе проиллюстрировано решения задачи выбора методов контроля качества изготовления деталей и узлов энергетического оборудования с помощью аппарата нечеткой логики. Рассмотрены основные методы неразрушающего контроля для выявления поверхностных и внутренних дефектов, а также освещены основные показатели качества металлоизделий. Проведен обзор видов дефектов металла и сварных соединений. Выполнено описание оборудования и средств контроля для выявления дефектов. Подробно описано последовательность и методика контроля качества ультразвуковым, капиллярным и магнитопорошковая методами контроля. Получены результаты контроля качества деталей при производстве и в процессе их эксплуатации. Проведен анализ выявленных дефектов. Приведены пример использования комплексного подхода к выполнению контроля. Проанализированы полученные результаты контроля процента совпадения выявления дефектов на изделии. Проведен комплексный контроль качества визуальным, ультразвуковым, капиллярным и магнитопорошковым методами неразрушающего контроля для определения процента совпадений выявления дефектов. Посредством создания эвристического анализатора на базе интерфейса системы нечеткой логики Fuzzy Logic Toolbox программы Matlab рассмотрен пример определения комбинации методов неразрушающего контроля для контроля качества вкладыша подшипника паровой турбины. Проведено компьютерное моделирование по методу Mamdani, который состоит из фаззификации с определением диапазонов изменения входных величин для каждого примера, задачей функций распределения для каждого входного параметра; вычисления правил, исходя из адекватности модели; дефаззификации с переходом от лингвистических термов к количественной оценке и графического построения поверхности отклика. Моделирование позволило определить оптимальную комбинацию методов неразрушающего контроля, которая обеспечивает высокое качество обнаружения дефектов вкладыша подшипника паровой турбины.

Ключевые слова: объект контроля; дефект; неразрушающий контроль; нечеткая логика; эвристический анализатор; фаззификация; дефаззификация; контроль качества.