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METHODOLOGY OF USING STANDARD SPECIMENS WITH DEFECTS FOR EDDY CURRENT INSPECTION: CLASSIFICATION, TYPICAL EXAMPLES, SIGNALS RESEARCH AND STATISTICAL METHOD FOR PARAMETERS ASSESSMENT

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ABSTRACT

The work was aimed at development of a methodology for using reference standards (RS) with defects to ensure high reliability and repeatability of eddy current flaw detection results. A classification of reference standards with defects is proposed and relevant examples are given to confirm the validity of the proposed classification. As an example, designs of composite multi-valued reference standards are presented for simulating surface and subsurface defects in cylindrical and flat objects under eddy current testing. New designs of composite reference standards are shown that simulate defects with different depths of occurrence. A corresponding set of RSs is presented that simulate a subsurface crack of the same size with 4 values of its depth of occurrence, and the corresponding double-differentiation eddy current probe signals are experimentally investigated. A proposed method for manufacturing reference standards for simulating inclined cracks is presented. A number of studies are analyzed that consider possible reasons for the difference between eddy current probe signals from a natural crack and artificial defects. By means of calculations using the method of volume integral equations, it is shown that the main reason for the difference between eddy current probe signals from natural fatigue defects and artificial defects is their width (opening). The influence of the crack length on the features of the parametric type eddy current probe signal is considered, which must be taken into account when choosing the length of the cracks of the reference standards to ensure the sensitivity threshold and reproducibility of the inspection results. A statistically based method for reliable estimation of the parameters of the reference standards with natural defects is presented, which has been successfully used to evaluate reference standards with fatigue cracks in tubular specimens.

KEYWORDS: reference standard, classification, eddy current method, non-destructive testing, eddy current probe, artificial defect, defect parameters

INTRODUCTION AND STATE OF THE PROBLEM

Metrological support methods and means have an important role in achievement of a high validity and repeatability of the results of eddy current flaw detection [1–3], with two approaches being possible here. Most often used for defect simulation are reference standards (RS) with artificial defects (AD) with the specified geometrical parameters, among which the most often normalized is the sensitivity threshold, i.e. the minimal AD depth, which should be revealed by the eddy current flaw detector (ECFD). Parameters of AD in RS should correspond to the requirements of technical documentation as to ECFD sensitivity threshold and conditions of its determination (distance from the eddy current probe (ECP) to the tested object (TO) surface, electrical-physical characteristics (specific electric conductivity and magnetic permeability) of TO material, TO thickness, etc). Scanning the TO surface using ECP, a metrologist or flaw-detection operator can assess the ECFD correspondence to the normalized characteristics as to sensitivity to the defects. Another rare approach is based on the use of electronic defect simulators, the simulation windings of which generate an electromagnetic field or signal, identical to those generated by eddy currents in a TO with a defect.

The problems of metrological support of ECFD using RS are not given due attention. In publications and standards on nondestructive testing (NDT) a great variety of terms could encountered for a long time: “test specimen”, “control specimen’, “standard specimen”, “standard”, “calibration standard”, “standard calibration specimen”, “simulator”, etc., which confirms an absence of common approaches. In English-language publications different terms are also used, in particular “reference standard” [4], or “reference block” [5]. And only in the last decades the term “reference standard” became the most commonly used for flaw detection RS. In keeping with the generally accepted metrological terminology [6], “a reference standard of the composition or properties of a substance (material) is a measurement means in the form of a specified amount of substance or material, designed for reproduction and storage of dimensions of quantities, characterizing the composition or properties of this substance (material), the values of which were determined as a result of metrological certification, which is used to transfer the unit size during verification, calibration, graduation of measuring instruments, certification of measurement procedures, and has been approved as RS in accordance with the established procedure". It is obvious that the above term does not take into account the specifics of flaw detection by NDT methods. However, there also exists a metrological term "measure, as a measurement instrument, which implements reproduction and (or) preservation of a physical quantity of the specified value" [6]. This term is more suitable for means for reproducing the physical quantity, used as the base for the NDT method than for specimens with AD. Important examples can be specimens for magnetic structural analysis instruments based on determination of the parameters of the magnetic hysteresis loop [7] or specimens of specific electric conductivity (SEC) for eddy current structuroscopes [8]. Unfortunately, the use of the term "measure"' is not an established practice in NDT metrology yet. This is confirmed by a discussion between the authors of the invention "Measure of the coercive force for metrological support of coercimeters with attached sensors" (authors are V.M. Uchanin, V.G. Rybachuk, S.M. Minakov, R.M. Solomakha) and experts of the State Patent Examination Office, who refused to issue a patent with such a title at first. However, the authors managed to defend their position, and today the patent is pending.

The above definition of the "reference standard" is very general and it does not take into account the features of flaw detection NDT, which is important to ensure a high reliability and repeatability of the obtained results. Therefore, for flaw detection RS used in NDT, the following definition is formulated: "A flaw detection reference standard is a product with normalized metrological characteristics for reproducing the property of TO discontinuities to generate a signal from primary transducer of the specified NDT technique". Such a definition underlines the main requirement to flaw detection RS: to adequately reproduce the features of simulated defects and TO design features. On the other hand, RS for flaw detection is a physical model of the material discontinuity, having a regular geometric shape and adequately replacing the material discontinuity during adjustment or calibration of NDT means. This definition implies a certain contradiction, because the RS, as any model, cannot fully reflect all the properties of the real TO. The adequacy problem should be solved, taking into account the special features of the defined problem and NDT technique. In particular, the RS for NDT should take into account the physical phenomena, on which a specific NDT method is based. As an example, we can give RS for ultrasonic testing, made from materials with the respective acoustic characteristics (for instance, organic glass), neglecting the TO electrophysical characteristics, in particular, their specific electric conductivity and magnetic permeability (MP). Accordingly, the difference in the acoustic characteristics of the RS and TO material can be neglected for eddy current testing. For this method, it is important to ensure the RS electrophysical characteristics, in particular their SEC and MP, which should correspond to TO material characteristics. The simplest way to ensure the adequacy of electrophysical characteristics is to make RS from the same material as the TO. Here, the RS production technology (in particular, the surface and heat treatment) should provide the respective material structure and stability of its electrophysical characteristics in time, which is related to physical aging of the material and to wear of the surface layer. Another requirement to RS is the possibility of making AD with established parameters with the specified accuracy, which is necessary for reproducing them when manufacturing a batch of RS. Not less important is the possibility of measurement of the normalized AD parameters for their metrological evaluation.

Let us remember that a new Law of Ukraine on metrology and metrological activity came into effect since 2016 [9], which changed the meaning of many metrological terms with the purpose of their harmonization with the international metrological practice [10]. The new law introduced the concept of "legislatively regulated metrology", which covers the types of activity, which are subject to state regulation as regards measurements, units of measurement and measuring equipment (ME). Metrological operations in the enterprises are concerned with ME metrological confirmation, which is understood as a set of operations, required to guarantee that ME conforms to the metrological requirements for its intended use. At the national and international levels ME metrological confirmation envisages conducting metrological operations, namely their testing and calibration. The "testing" term corresponds to "verification", which means obtaining objective evidence that this ME corresponds to the established requirements. From 1993 till 2015 the "verification" term referred to ME, which are subject to state metrological supervision. In addition, starting from 2016 there separately exist ME in the sphere of legislatively regulated metrology and other ME, which are not covered by legislatively regulated metrology. There is an analogy with the state and departamental verification of ME, which existed up to 1993. At the same time, there is an expectation that the basic methodology of RS application in eddy current flaw detection defined below will be relevant, irrespective of the changes in the legislation of Ukraine.

This paper is an attempt to initiate the creation of the methodology of RS application in eddy current flaw detection. In particular, an RS classification with the respective examples is proposed, a range of engineering solutions is given for RS for simulation of subsurface and inclined defects, the influence of RS defect width and length on ECP signal was studied and a statistically substantiated method to determine the parameters of RS with natural defects is presented.

CLASSIFICATION OF FLAW DETECTION REFERENCE STANDARDS

To develop the methodology of RS application for metrological support of ECFD, we will consider the possible RS variants based on their classification, where the following features were used as the classification characteristics: type and origin of the defects; AD producing technology; main normalized parameters and number of normalized values; design, as well as the stage at which they are used (Figure 1).

Flaw detection reference standards can be produced using natural or artificial defects (Figure 1). It is obvious that the real conditions of defect detection are best reproduced by RS with natural defects, arising during the production cycles (melting, casting, deformation stamping, heat and chemical-thermal treatment; machining, welding) or during operation (fatigue cracks, corrosion damage of different types, etc.). The disadvantages of RS with fatigue cracks, in particular, is the problem of introducing cracks with specified geometrical parameters with guaranteed accuracy. The possibility of determination of the fatigue crack parameters during metrological evaluation is also limited, because of their small opening (width). Accurate characteristics of RS with natural defects can be determined only after their fracture. That is why in practice RS with AD of a simple shape are traditionally used for testing and tuning of the NDT means [11–13]. An advantage of such RS is the simplicity of their production and metrological evaluation, which is performed by measurement of AD normalized parameters by the methods of linear dimensions measurement.

Irrespective of their origin, the defects are usually divided into elongated (linear) and local (bulk). A defect, for which the ratio $l_{CR} >> a >> c$ is valid, where l_{CR} is the crack length, a is its depth and c is its width, is usually called a crack. These parameters are close for local defects (for instance, pores). Elongated cracklike AD are predominantly simulated by slots (cuts), made by electric spark method or a thin mill. The thinnest slots, which reproduce a natural crack better, are made by electric spark method, which creates defects of up to 0.1 mm width (opening). Pro-

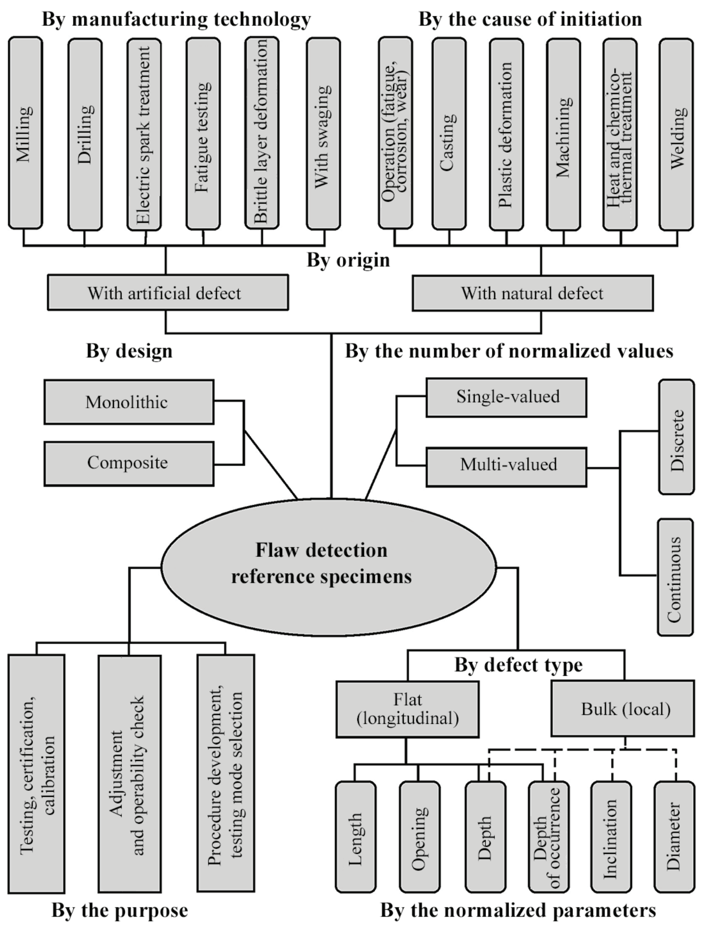

Figure 1. Classification of reference standards in flaw detection

ducing AD by milling is simpler, but it does not allow making AD of less than 0.2 mm width. Opening of such an AD is reduced by swaging, for which the material ductile properties are enhanced by heating [11]. Local volume defects of the type of a pore or corrosion pit are usually simulated by drilling with a flat bottom [14, 15].

A disadvantage of RS with AD is the fact that by their properties, and, what is particularly important, by the ability to form the respective ECP signal they differ from RS with natural defects (in particular, fatigue and corrosion defects). In some cases, in order to reproduce the fatigue crack properties, they are formed by cyclic loading in mechanical testing machines. For longitudinal cracklike defects the main parameters normalized during RS certification can be their depth, depth of occurrence for subsurface defects or inclination of the defect plane relative to the TO surface. For local defects, the normalized parameters are: depth, diameter, depth of occurrence or inclination relative to the controlled surface for subsurface defects.

By the number of values of the reproduced normalized defect parameter, the RS can be single or multi-valued (Figure 1). That is, RS can simulate one or several defects with different values of the normalized dimension. Multi-valued RS can reproduce discrete or continuous values of the normalized defect parameter in the range of its change. In terms of design the RS can be made as a monolithic specimen or they can be composed of two or more parts. Composite RS are most often used to simulate the subsurface defects [16–18].

Figure 2 shows a composite RS for simulation of subsurface defects in cylindrical TO. RS in Figure 2, *a* is made in the form of a layered cylinder with AD in the form of a cut along the cylinder generatrix in one of the layers [16]. The AD depth is assigned by selection of the thickness of a cylindrical layer with a through-thickness AD, and the depth of its occurrence is specified by selection of the outer layer thickness. Such an RS reproduces only one value of AD depth and one value of the depth of its occurrence, i.e. discrete values of AD parameters. It cannot simulate the AD differing by their depth and with different depth of their occurrence. For this purpose, it is necessary to create individual RS, which will simulate discrete values of the respective parameters.

More versatile is a composite RS in Figure 2, *b* in the form of eccentric bushings *1*, *2*, between which cylindrical bushing *3* with AD *4* is located [17]. By turning the bushing of such an RS it is possible to change the depth of AD occurrence in a certain range with the constant dimensions of AD and thickness of the cylindrical TO, i.e. this RS is a multi-valued measure of the depth of defect occurrence. Its disadvantage is the

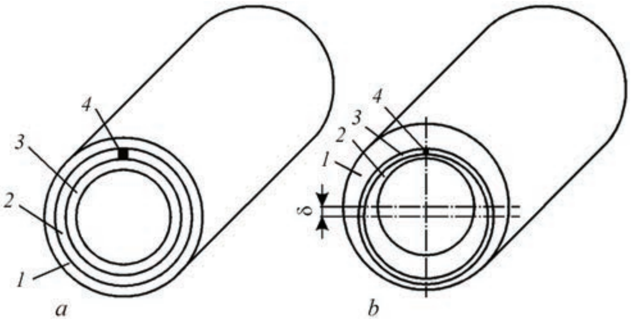

Figure 2. Single-valued discrete (*a*) and multi-valued (*b*) RS of composite type for simulation of the defects of the cylindrical TO: *1–3* — layers of cylindrical RS; *4* — AD; δ — eccentricity

complexity of manufacturing this RS, as to achieve a tight connection of the bushings, it is necessary to ensure their accurate dimensions along the entire specimen length. Otherwise, there will be gaps between the layers, which will influence the ECP signal.

Flaw detection RS can be classified according to their purpose, as they are designed to endure the testing validity by: 1) ECFD testing, certification and calibration; 2) setting up and periodical checking of ECFD operability for performance of a specific testing procedure; 3) selection of the testing modes during development of the procedure, taking into account the TO features and the factors creating interference (Figure 1). The procedures of ECFD testing, certification and primary calibration are an important stage of developing them, during which the metrological characteristics (predominantly, sensitivity threshold and resolution) are normalized. This stage is subject to metrological supervision by accredited institutions using RS, which have passed the respective metrological assessment. Such RS are proposed by the ECFD developer or the accredited institution, so they are often called primary. Checking of ECFD adjustment and its ability to perform the procedure of testing a particular product is conducted directly in the work place. Here, RS are used, which maximally reproduce the TO features. The parameters of AD of such defects are chosen, depending on the selected rejection criterion, which can differ from ECFD sensitivity threshold. These RS should simulate the features of the entire range of the factory TO, and in practice they are most often made by the companies operating the NDT means. Such RS are often defined as secondary RS. They are not always subject to metrological assessment and, in the best case they pass technical inspection for compliance with drawings. At the research stage the fundamental possibility to solve a new NDT task is determined, testing modes are selected (for instance, ECP type, operating frequency, etc) and the testing procedure is optimized, allowing for the TO design features. Here, RS are required

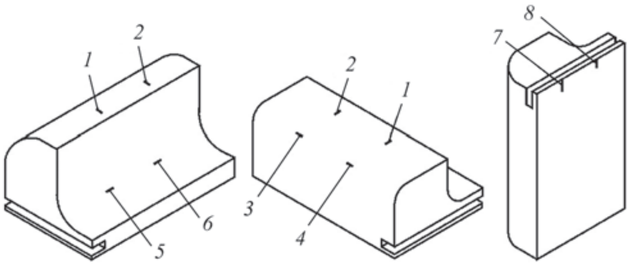

Figure 3. RS of SOP type with surface defects in the plane (*1*, *2*), convex (*3*, *4*), concave (*5*, *6*) and edge (*7*, *8*) sections

which completely reproduce the conditions of testing of a particular product (SEC, MP, availability of the coating, surface curvature, design features, etc.). These RS do not require metrological assessment, as they are not used after research is completed.

In order to implement the technologies of quantitative flaw detection with determination of the parameters of the detected defects, the metrological support (including approaches to RS selection) should change essentially. In today's practical work the ECFD are certified only using RS with AD, which characterizes the sensitivity threshold. For quantitative flaw detection it is necessary to develop RS, which reproduce AD parameters in the range of their change and to assess the error of their determination.

In reality, the conditions of the influence of a number of parameters changing the ECFD limit sensitivity are controlled. Strictly speaking, ECFD sensitivity threshold is a function of many parameters (for instance, the gap between ECP and TO surface, distance to TO edge, SEC and TO thickness). A methodologically correct approach would envisage normalizing these influences to assess the possibility of flaw detection in the real conditions. Such an approach, however, is not applied in practice, as it requires a large set of RS.

In practice, the simplest flat RS are used, with a slot made across their entire width, the depth of which corresponds to ECFD sensitivity threshold. Such an RS evaluates the sensitivity threshold only by depth. An essential drawback is the impossibility to establish ECFD sensitivity threshold only by the defect length. More over, the influence of the surface and edge curvature is not assessed. Better possibilities are provided by RS with surface defects, made from aluminium alloy D16 (SOP 5-1), titanium alloy VT3 (SOP 5-2) and ferromagnetic steel St45 (SOP 5-3), earlier used to fit ECFD of PROBA-5 type (Figure 1) [12]. Slots 2 mm long with up to 0.1 mm opening were made by electric spark method with 0.05 mm thick brass electrode. Slots 0.2 mm and 0.5 mm deep were made on the surface of RS from the aluminium alloy, slots 0.5 and 1.5 mm deep were cut in RS from the titanium alloy and steel. In addition to slots on RS flat surface (Figure 3, defects *1*, *2*), slots were made on the cylindrical convex (defects *3*, *4*) and concave (defects *5*, *6*) sections of 6 mm radius. In addition, two defects 0.5 and 1.0 mm long (defects *7*, *8*) were introduced on RS edge. Thus, such RS enable assessment of ECFD sensitivity by the depth and length of the surface AD on the flat and curvilinear surfaces in ferromagnetic steels and non-ferromagnetic materials with different SEC. A disadvantage of this RS is the complexity of manufacturing and high cost, making it impossible to fit every ECFD with them. Nonetheless, these RS were successfully used by us during state trials of eddy current autogenerator flaw detectors of LEOTEST VD type, which were conducted at SC "Dniprostandardmetrologia" (Dnipro city) [13].

European standard on checking the ECP characteristics proposes the general requirements to RS, the set of which for testing the surface: ECP is given in Figure 4 [5]. Each of the RS should have the length and width minimum ten times greater than that of ECP sensitivity zone. If this characteristic is unknown, it should be replaced by the maximum (active) ECP size in the scanning plane. The distance from the slot to RS edge should be 2.5 times greater than the extent of the edge influence zone. RS thickness should be minimum two times greater than the standard penetration depth of eddy currents at ECP lowest operating frequency. More detailed requirements to each specific RS, in particular slot number, slot width and depth and hole diameter, should be specified in the testing procedure or operating documentation. To study the ECP signals from elongated defects RS of A1 type was proposed (Figure 4) with a slot in the central zone, which should be longer than the minimal length of the slot, exciting the maximal ECP signal, and deeper than the minimal depth of the surface slot, exciting the maximal ECP signal. To study ECP signals from local defects, RS of type A2 with a hole in the central zone was proposed. It is recommended that the hole depth is equal to that of the slot in block A1. RS set of type A3 is proposed to assess the

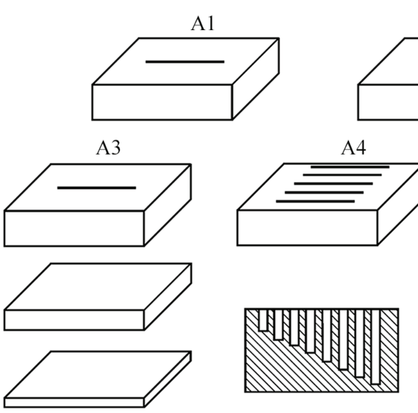

Figure 4. RS for checking the characteristics of put-on ECP in keeping with a European standard [5]

influence of thickness, in particular, effective depth of eddy current penetration. They are similar to specimen A1 without a slot with different thickness, increasing to three values of standard penetration depth or to two ECP active dimensions. This RS together with such of A1 type, is also used for determination of effective depth of subsurface defect detection. In keeping with the proposed classification a composite RS is used here, in which selection of plate thickness is used to simulate different TO thickness. To assess the influence of slot depth, in particular, to determine the minimal depth, exciting the maximal ECP signal, RS of type A4 are proposed (Figure 4). It is similar to A1 specimen, but it has a set of parallel slots, located in RS center. Here, all the slots have the same length and width (as in RS A1), and the depth is gradually increased with a constant step. The distance between two successive slots should be at least 5 times greater than the size of ECP sensitivity zone. RS of type A5 (4) were proposed to assess the influence of defect length on ECP signal, in particular, to determine the minimal length, ensuring a constant ECP signal. It is similar to specimen A1, but with a series of parallel slots, having the same depth and width as do the slots in specimen A1, but their length gradually increases with a constant step. The distance between the two successive slots should be at least 5 times greater than the dimensions of ECP sensitivity zone.

Let us remind you that in keeping with the European standards these RS are designed for ECP characterization, which is required to select the respective ECP to solve the defined task at the stage of development of the testing procedure, and not for ECFD metrological assessment. They enable determination of the minimal depth and length of the crack, generating the maximal ECP signal. They allow establishing the testing locality (by the sensitivity zone dimensions), studying the influence of ECP orientation relative to the crack, influence of TO thickness, etc. They however, do not provide evaluation of the resolution, which requires RS with defects located at different distance. The resolution in this case can only be assessed indirectly by the dimensions of the sensitivity zone. The European standard also envisages application of a composite RS, where the defect is simulated by a butt of two ground plates. This RS variant has traditionally been used to study ECP signals with different depth of occurrence, as well as to optimize the procedures of testing multilayered aircraft components.

MULTI-VALUED COMPOSITE RS FOR SIMULATION OF THE SURFACE AND SUBSURFACE DEFECTS IN CYLINDRICAL AND FLAT TO

Most of the known RS can be used only for surface defect simulation. Implementation of the technologies of detection and evaluation of hidden subsurface defects at low operating frequencies requires RS with AD, which have been additionally normalized by the depth of their occurrence. We proposed a multi-valued composite RS (Figure 5) to simulate surface and subsurface defects for rotary testing of cylindrical TO (V.M. Uchanin, V.L. Naida, I.I. Kyrychenko, O.M. Gogulya. Standard specimen for adjustment, calibration and certification of eddy current flaw detectors. Pat. of Ukraine No. 39172. Publ. 10.02.2009). RS for surface defect simulation consists of two cylindrical tubular parts *1* and *2* with outer diameter *D*, internal diameter *d* and wall thickness *T*. For simulation (Figure 5, *a*) one end of cylindrical tubular part *1* was treated on end section 3 of length *l* over the conical surface so that the outer diameter of end section *3* increased from the tube end along the length of section *l* at specified angle α° relative to cylinder surface. Part *2* of the specimen was treated on end section *4* of length *l* over the conical surface so that the internal diameter of end section *4* decreased from the tube end along the length of section *l* at the same angle α°. Both the RS parts are connected over the conical surfaces of end sections *3* and *4* so that they form a single cylinder. To simulate the surface cracklike defect, a thin through-thickness cut of length *l* and width *c* is made in the end conical section *4* of RS second part. As a

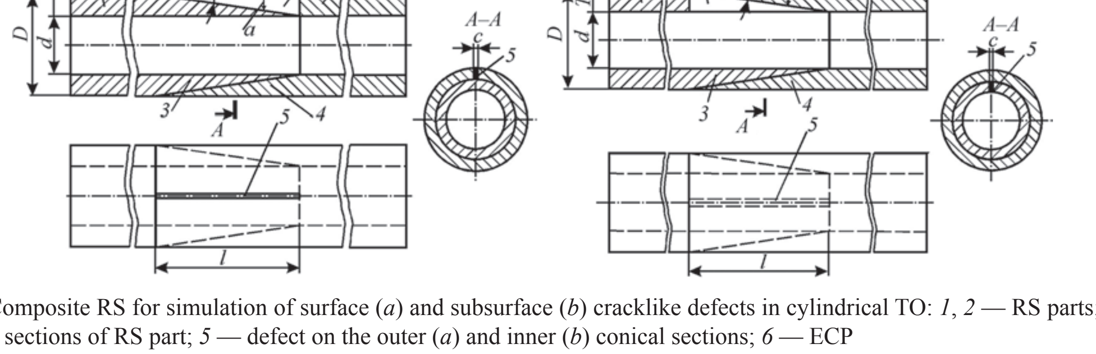

Figure 5. Composite RS for simulation of surface (*a*) and subsurface (*b*) cracklike defects in cylindrical TO: *1*, *2* — RS parts; *3*, *4* — conical end sections of RS part; *5* — defect on the outer (*a*) and inner (*b*) conical sections; *6* — ECP

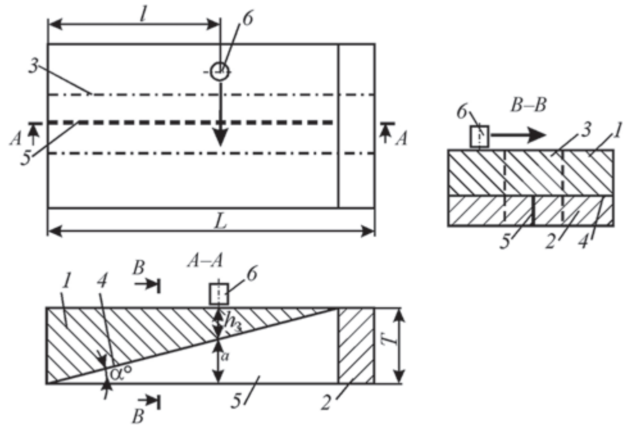

Figure 6. Composite multi-valued RS for simulation of surface and subsurface defects in flat TO with a weld: *1*, *2* — wedge-shaped parts; *3* — weld area; *4* — butt; *5* — AD; *6* — ECP

result, the RS simulates the surface defect, the depth of which a changes from 0 to T, depending on the position of rotary ECP along the RS (Figure 5, *a*).

To simulate a subsurface crack (Figure 5, *b*) a thin through-thickness cut of length l and width c is made in end conical section *3* of first part *1*. After joining the RS parts over conical surfaces *3* and *4* a subsurface defect of length l and width c is simulated, having variable depth of occurrence h_{occ} from 0 to T. To simulate a bulk local defect of pore type, holes of different diameter can be drilled out in RS end sections.

RS in Figure 5 are simple to produce and they simulate defects of different type and size, located at different distance from the TO surface. The defect depth or depth of its occurrence in the tested zone are determined by the position of rotary ECP *6* along RS defective section, so that this RS, in keeping with the classification (Figure 1) is a composite multi-valued one.

A composite multi-valued RS (Figure 6) was proposed to simulate subsurface defects of different depth and depth of occurrence in flat TO. It contains two wedge-shaped parts *1* and *2* having the same angle of inclination α (V.M. Uchanin, V.G. Rybachuk. Standard specimen for adjustment and certification of eddy current flaw detectors. Pat. of Ukraine No. 39189. Publ. 10.02.2009). RS parts are abutted in plane *4* so as to form a plate with plane-parallel surfaces. To simulate cracks, thin cut *5* is made in one of the wedge-shaped parts. The cut plane is normal to

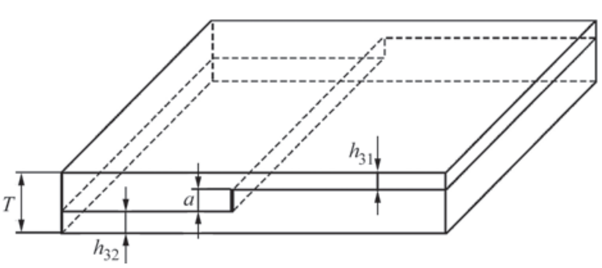

Figure 7. Composite RS for simulation of two discrete values of the depth of defect occurrence

butt plane *4* of wedge-shaped parts. When ECP is installed on RS surface, which belongs to wedge-shaped part *1* without a cut (Figure 6), a subsurface crack is simulated with variable depth of occurrence h_{occ} and variable depth a, which depend on distance l between the ECP and the RS edge of length L. When ECP *6* is installed on RS surface, which belongs to wedge-shaped part *2* with a cut, the AD simulates a surface crack. AD depth a changes, depending on distance l between the ECP and the RS edge. One can see from Figure 6 that depth of occurrence h_{occ} of the crack and its depth a depend on distance l between the ECP and the RS edge, according to relationships $a = l \cdot \mathrm{tg}\alpha$ and $h_{occ} = T - a = T - l \cdot \mathrm{tg}\alpha$. Changing ECP distance l from RS edge, we can simulate the surface and subsurface cracks of different depth and depth of occurrence in a certain continuous range of these parameter values. If required, a linear scale of the simulated parameter can be applied to the RS surface.

To simulate defects of the type of lacks-of-penetration in the welds, the RS wedge-shaped parts were produced from plates with a weld made in advance (dashed line in Figure 6). The direction of inclination of RS wedge-shaped parts coincides with that of the weld. AD in the form of a cut was introduced in wedge-shaped part *2* in the weld area.

There exist situations, when it is enough to simulate the discrete values of the defect parameter. In particular, in order to study the influence of the depth of defect occurrence, irrespective of its dimensions, it is possible to use RS, which simulates a defect of the same depth for two discrete values of the depth of occurrence (Figure 7) [19]. The two parts of the RS are put together so that after they are combined, a rectangular plate of thickness T formed with a subsurface defect of depth a. The defect is a butt of the two parts, normal to the specimen surface. The depths of defect occurrence h_{occ1} and h_{occ2} are different relative to different surfaces of the specimen, in keeping with relationship $h_{occ1} + h_{occ2} + a = T$. Two RS from D16T aluminium alloy 7 mm thick were made: one simulates a 2 mm deep crack, located at depths of 2 and 3 mm; and the other is a 2 mm deep crack located at depths of 1 and 4 mm.

Such a set of RS allows simulation of four values of the depth of occurrence of a defect of the same size, and studying the influence of the depth of its occurrence on ECP signal, irrespective of the plate size and thickness. ECP signals for these RS were studied using an eddy current board EDDYMAX. Figure 8 gives the signals of ECP of MDF 0801 type in a complex plane at operating frequency of 1 KHz. The gain for AD with the depth of occurrence $h_{occ} = 1$ and 2 mm was equal to 44 dB. For defects with $h_{occ} = 3$ and 4 mm (Figure 8, *c*, *d*) the gain was increased by 12 dB, con-

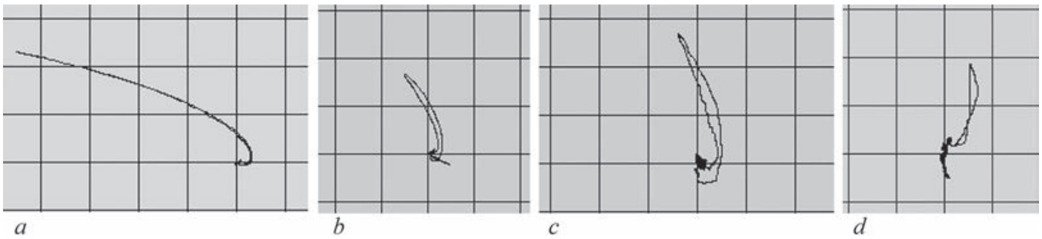

Figure 8. ECP signals from an extended cracklike defect with depth of occurrence h_{occ} (mm): 1 (*a*); 2 (*b*); 3 (*c*); 4 (*d*)

sidering the large difference in the amplitude of the signal for AD with different depth of occurrence.

The given results illustrate the principle of RS application (Figure 7) to determine the potential of eddy current method, in particular, for detection of cracklike defects of depth a = 2 mm, occurring in aluminium alloy products at up to 4 mm depth. One can see that at 1 kHz operating frequency the selected ECP provides a reliable detection of all the RS defects of 2 mm in-depth size, occurring at up to 4 mm depth in aluminium alloys. With increase of AD depth of occurrence, the ECP signal amplitude decreases essentially. Here, with increase of the depth of occurrence, the hodograph of ECP signal rotates clockwise, i.e. the phase of ECP signal changes, which should be taken into account during development of the testing procedure. The described set of composite RS was used to study and develop a procedure for detection of internal defects in multilayer aircraft structures and in welded joints of aluminium alloys.

MANUFACTURE OF RS FOR SIMULATION OF INCLINED DEFECTS

Most of the known RS can only be used to simulate surface defects, oriented normal to TO surface. This can be explained by that such defects are characteristic for the majority of structures, although known are cases of inclined crack formation, in particular, with contact interaction of surfaces during rolling [20]. In a few cases, RS with defects oriented at a specified angle to TO surface are required to detect and evaluate defects of different orientation. The known methods of producing RS do not allow introducing inclined AD with a specified angle of inclination, because when trying to introduce them thin mills are deformed and the cutting process becomes unstable, particularly at smaller (less than 60°) angles of the mill inclination relative to the surface. In order to create RS with inclined defects, a method of their production is proposed (V.M. Uchanin. A method to produce standard specimens for adjustment, calibration and certification of nondestructive testing instruments. Pat. of Ukraine No. 29293. Publ. 10.01.2008). In order to implement it, first a material is selected with electrophysical characteristics (SEC and MP) corresponding to TO, from which billet *1* is made (Figure 9). Wedge-shaped notch *2* is made on the billet surface, the side surface of which is inclined at angle φ relative to the billet surface. After that AD in the form of thin slot *3* is made by electric spark method or a thin mill on the notch side surface (Figure 9, *a*). Then, part of the billet together with the notch is removed along line *4* (Figure 9, *a*), forming the RS surface. The produced RS simulates a cracklike defect inclined at angle φ (Figure 9, *b*). Selection of angle φ, depth of the cut, made on the side surface of the notch, and the thickness of the removed layer of the billet allows simulating defects of different depth with different inclination relative to the surface. Using RS with inclined defects is important for investigation and optimization of eddy current procedures for quantitative evaluation of inclined crack parameters [21].

ANALYSIS OF THE POSSIBLE CAUSES FOR THE DIFFERENCE BETWEEN ECP SIGNALS FROM ARTIFICIAL AND NATURAL CRACKS AND INVESTIGATION OF THE INFLUENCE OF CRACK WIDTH ON ECP SIGNAL

The authors [22] believe that the natural cracks and AD in the form of thin slots create ECP signals close as to their characteristics. At the same time, a large number

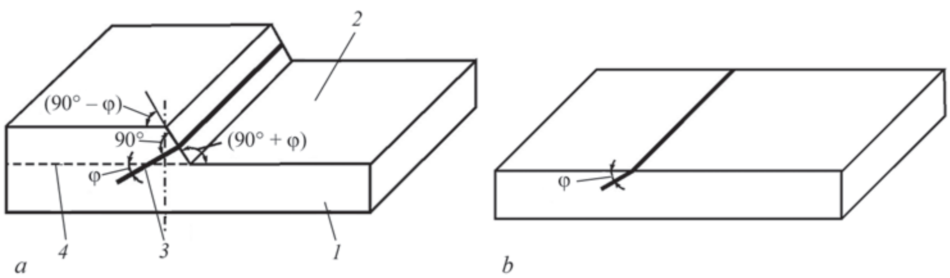

Figure 9. Scheme of implementation of the production method (*a*) of RS for simulating inclined cracks (*b*): *1* — billet; *2* — wedge-shaped notch; *3* — defect; *4* — line of notch removal

of works on this issue report a significant difference in the ECP signals from natural defects and AD [23–27]. Among the causes given to explain the possible discrepancies are: 1) presence of a plastic strain zone in the natural crack zone [23]; 2) greater value of AD opening, compared to a natural crack [24, 27]; 3) possibility of electric contact of the natural crack walls, unlike the AD, where the possibility of such a contact is absent [26]; 4) greater roughness of the natural crack fracture surface, unlike the AD, which has smoother walls [28]. Let us consider the differences in ECP signals from the natural defects and AD in greater detail.

Traditional models of ECP signal formation do not allow for changes in electrophysical parameters of the material in the zone of plastic strains, generated by the fatigue crack. In [23] the authors believe that the width of this zone is large enough, and it can be much greater than the volume of the crack proper. This leads to considerable changes of SEC and MP in the defect zone, which can influence the ECP signal. No experimental proof of such influence is given, however.

Greater roughness of the fatigue crack fracture surface, unlike the AD with smooth walls characteristic for electric-spark AD, also can be one of the causes for the difference in the signals. It is known that the rough surface of the fatigue crack is of a fractal nature [29–31]. In [28] the influence of the fractal nature of the natural crack fracture on ECP signal is considered. One of the variants of Koch surface is used as a simple model of crack fracture [32]. It is shown that increase of fractal dimension D of the natural crack fracture surface (D > 2), compared to the AD smooth surface dimension (D = 2) leads to an increase in electric resistance to eddy currents in the crack zone. However, no experimental proof of the significance of such an influence is given either.

In the majority of the works [24–27] it is shown on the base of experimental studies that the signals from AD are significantly higher than those from natural cracks. In [24], in particular, it is noted that the signal from AD can exceed 2–5 times the signal from the natural crack of the corresponding depth. It is shown that the signals from a natural crack have a higher variability, compared to those from AD, and that there also exists the dependence of discrepancy between the parameters of the signal from AD and from the natural crack on the operating frequency, when the difference between the ECP signals from natural defects and from AD becomes greater with the increase of operating frequency. The authors of these works assume that the main cause of the discrepancy between the signals from the natural defects and AD is the different opening of the defects, as the signals from the natural cracks with a small opening and the AD in the form of slots of a rather large width were compared. Note that the conducted experiments could have given erroneous results, as with the equal depth and length of the compared natural defects and AD a similar value of their width (opening) was not provided, because of the lack of the necessary specimens. To confirm this conclusion on the decisive influence of AD width on ECP signal, it is important to conduct the respective theoretical studies.

To study the influence of the defect width (opening), calculation of the hodographs of the signals of parametric ECP was performed by the method of volume integral equations [33–34] for a crack of the same depth and length with a change of its width. Signals from a crack 5 mm long and 1 mm deep located in a nonmagnetic halfspace with SEC of 20 MS/m at operating frequency of 1 MHz were studied. Winding of the studied ECP consisted of 20 turns 0.5 mm high with internal and outer radii of 0.45 and 0.55 mm, respectively. The obtained values of ECP impedance during its interaction with the defect were normalized relative to ECP impedance, in case of its mounting on a defectfree halfspace with SEC of 20 MS/m (R_{20} = 0.174 Ohm; X_{20} = 1.806 Ohm and L_{20} = 0.287 μH). All the geometrical parameters together with opening c were normalized relative to ECP mean diameter (1 mm). Calculations were performed for relative opening values c' from 0.01 to 2.4, that corresponds to possible opening of the natural and artificial defects. Note that the AD are most often made with up to 0.3 mm opening, which in our case corresponds to the reduced value c' = 0.3. Derived results (Figure 10) indicate that the ECP signal amplitude significantly depends on the crack opening. With its increase from 0.01 to 0.3 the amplitude increases by an order (from 0.0026 to 0.083), and the signal phase changes from 62 to 82°. With increase of the opening from 0.01 to 2.4 the signal amplitude increases by two orders (from 0.026 to 0.26), and the phase changes from 62 to 103°.

The obtained calculation results confirmed the conclusion about the decisive influence of the defect width on the difference in ECP signals from the natural defects and the AD. During preparation of RS simulating the fatigue cracks, it is important to make AD with a small opening. The advantage should be given to methods of swaging the RS with an artificial defect to reduce its width.

INVESTIGATIONS OF THE INFLUENCE OF THE CRACK LENGTH ON ECP SIGNAL

Investigations of the influence of the crack length on ECP signal have a methodological importance for determination of the conditions of reproducibility of the testing results, when using the AD with cracklike defects. In metrology the reproducibility is a characteristic of measurement quality, which reflects the closeness of the results of measurement of one and the same value taken in different conditions [6]. Reproducibility is not less important for flaw detection, as it is a measure of comparability of testing results, derived at different locations by different flaw detection operators and testing means. Note that in addition to “reproducibility” term, a related term of repeatability is used in more recent documents. It reflects the similarity of measurement results under the conditions of repeatability, when independent test results were obtained by the same method on identical specimens in one laboratory and the same operator using the same equipment within a short time interval [35]. It is obvious that this term reflects the individual characteristics of the operator, in particular the level of his qualification.

The influence of crack length on ECP signal was studied in many works, which reported close results [36–41]. In [36] proceeding from the results of experimental studies on physical models of Wood alloy, it was mistakenly noted that the distribution of ECP signal from a long crack has two maximums in the zone of its ends in the absence of a central maximum, which is attributable to an insufficient accuracy of experimental investigations. It is obvious that the theoretical studies allow revealing the features, which can be overlooked during experimental investigations [37]. In [41] the investigations of ECP signal distribution were conducted in a broad range of the ratio of crack length to ECP diameter, their results being in good agreement with the research results of other authors [37–40]. In [41] a parametric ECP with one winding was studied during scanning of an electrically-conducting nonmagnetic TO with a crack in the form of a surface rectangular slot of length l_{CR}, depth a and width (opening) c ($l_{CR} >> a >> c$), located in the center of the system of coordinates, where coordinates X and Y correspond to the transverse and longitudinal directions relative to the crack, respectively. The changes in the amplitude of ECP signal Z_{CR} introduced by a crack were normalized relative to that of ECP impedance Z_{TO} in case of mounting on TO defectfree part: $Z'_{CR} = \Delta Z/Z_{TO}$. The geometrical parameters were normalized to ECP diameter D_c, i.e. the reduced crack length $l'_{CR} = l_{CR}/D_c$, and the reduced coordinate $y' = y/D_c$. Calculation of amplitude distribution along Y coordinate was conducted for an aluminium alloy with SEC σ = 20 MS/m at operating frequency of 1 MHz. Figure 11 gives the distribution of signal amplitude along the crack along its length by y coordinate for different ratios of the crack length to ECP diameter, namely: for short cracks with l'_{CR} = 0.3 (0) and l'_{CR} = 1 (●) and for long cracks with l'_{CR} = 4 (Δ) and l'_{CR} = 5 (▼). Obtained distributions of ECP signal amplitude in such a broad range of l'_{CR} thicknesses enable clearly emphasizing an essential influence of the crack length on the nature of spatial distribution of the amplitude of a signal from the crack. For short cracks the signal distribution has a two-hump symmetric character with a minimum at $y = 0$ (ECP over the crack center), which can reach zero for cracks of length $l'_{CR} < 0.3$. The ECP signal reaches its maximal value, when the short crack is located directly under the ECP turns in the zone of maximal eddy currents. The presence of two maximums for short cracks can be interpreted as signals from two separate defects. For long cracks, the distribution has one maximum, which corresponds to ECP position in the crack center. Further increase of the crack length from l'_{CR} = 4 will no longer influence the signal amplitude, as the distribution curves in this area actually coincide.

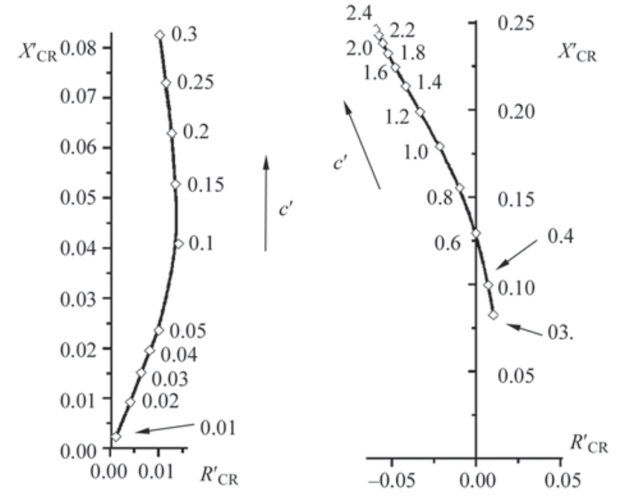

Figure 10. Hodograph of ECP signal from a crack, depending on its opening c' in the range from 0.01 to 0.3 (a) and from 0.3 to 2.4 (b)

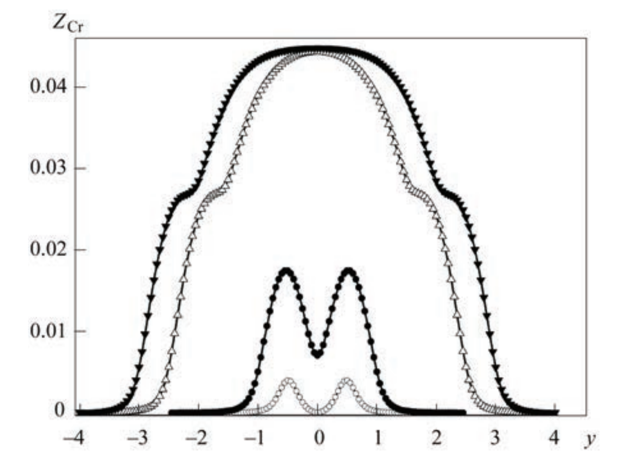

Figure 11. Distribution of the amplitude of a signal along the crack by coordinate y, depending on its length for short (l'_{CR} = 0.3 (0) and (l'_{CR} = 1 (●)) and long (l'_{CR} = 4 (Δ) and (l'_{CR} = 5 (▼)) cracks

Analysis of the given dependencies allows us to draw important conclusions as to selection of the crack length during RS development. Short cracks create a large variability of ECP signal during scanning of the crack zone. This makes it impossible to use RS with short cracks to assess the reproducibility or repeatability of the results of eddy current testing, as it is practically impossible to ensure the same conditions for result reproducibility during scanning of the crack zone by different flaw-detection operators. To assess the reproducibility or repeatability of test results, it is rational to use RS with long cracks, during the application of which a slight shifting will not have any significant influence on ECP signal. In this case, it is rational and much simpler to make RS specimens with a cracklike defect across the entire RS width.

At the same time, RS with short cracklike defects should be used to assess the sensitivity limit by the length of the cracks, which should be detected, in those cases, when it is important for the posed flaw detection task (see, for instance, RS in Figure 3).

PROCEDURE FOR STATIC ASSESSMENT OF REFERENCE STANDARD PARAMETERS

In order to create RS, it is possible to use natural defects, or defects formed during fatigue testing (Figure 1). The problem, however, lies in determination of the parameters of such defects, as they can be established with sufficient accuracy by direct measurements only after RS breaking up, when they are no longer suitable for metrological support of NDT instruments.

Known are the procedures of making the RS, where this contradiction is eliminated by studying the RS with breaking up of part of randomly selected specimens and assigning to the intact specimens the controlled parameter value determined by direct measurements [42]. The total number of the specimens and of those which are broken up is determined empirically, and the nominal value of the parameter is assigned to the intact specimens based on an unverified assumption of the homogeneity of the entire specimens. It is obvious that such a procedure is valid only when the scatter of the controlled parameter values is small for the majority of the specimens. In other cases, the controlled parameter value assigned to RS is insufficiently substantiated, as it can differ from the actual one with an undetermined error.

One of the possible variants of a comprehensive solution to the problem is application of a statistical approach, which was used for the first time to create RS for certification and verification of an instrument for measurement of the coefficient of charge filling in the flux-cored wire [43, 44], which was conducted in keeping with our invention (A.Ya. Teterko, O.L. Hodovnik, Yu.V. Pozdnyakov, V.N. Uchanin. A method for adjustment, calibration and verification of an instrument for controlling the flux-cored wire filling with the charge. USSR Auth. Cert. No.1569694. Publ. 07.06. 90). Furtheron a statistical method of RS certification and calibration was developed for other NDT problems, in particular those of flaw detection (V.N. Uchanin, Yu.V. Pozdnyakov, Yu.N. Agapov. A method to produce a measure for calibration of non-destructive testing instruments. USSR Auth. Cert. No. 1753394. Publ. 0.7.08.02). The proposed statistical approach provides assessment of the error of determination of the controlled parameter of intact RS, which were left for use, as it is based on the possibility of application for RS evaluation of a working NDT device which should be calibrated. Note that in flaw detection the defect depth most often in the controlled parameter. For eddy current flaw detection RS with fatigue cracks the proposed procedure can be presented as a sequence of the following operations [45]:

1) At the first stage a set of *N* specimens is selected which themselves can be the tested products proper or their fragments with natural cracks. The material and geometrical parameters of the selected specimens should be the same. During production of RS with cracks by the fatigue testing method it is desirable to select specimens with the same number of the loading cycles. The sufficient for the group *N* number of the specimens can be determined in advance, analyzing the scatter of the controlled parameter for specimens of this type.

2) At the next stage an ECFD is used, from which only a certain correlation between the output signal parameters and the controlled parameter of the crack is required (for instance between the signal amplitude and the crack depth). The operating frequency is selected to be such that there exists a dependence of the signal on the crack parameter (for instance, depth) in the specified range of change. RS with AD can be used for this purpose.

3) The selected specimens are controlled using the prepared ECFD and its readings are recorded for each specimen. After that the specimens are organized, arranging them in the order of increasing ECFD readings.

4) The first group of the controlled parameter (crack depth) is formed. For this purpose, *W* specimens are selected from the initial set *N* of the specimens, for which the values of instrument readings are close to minimal values. This is enough for the majority of indicator-type ECFD. For quantitative testing groups of specimens having medium and maximal ECFD readings in the range of change are formed similarly. In case of a large dispersion of the values of instrument

readings it is necessary to increase (for instance, double) the size of the specimen primary sample until W similar specimens are obtained for each group from the studied number of specimens.

5) Then, Q out of W specimens are selected randomly from each group, actual values X of the controlled of the parameter defect (depth) are determined by direct methods (for instance, using a measurement microscope) after their breaking up.

6) The estimate of the mathematical expectation of the studied parameter (depth) for each group of similar specimens is calculated by the following formula:

$$W_{ik} = 1 / Q \sum_{k=1}^{Q} X_{ik}$$

where i — is the group number; $k = 1, \ldots, Q$.

This estimate is taken as the actual value of the controlled parameter, reproduced by each group measure. After that, the value of mathematical expectation is assigned to the respective RS of the group based on the earlier established homogeneity of the specimens included into it.

Any of the intact specimens can be used for ECFD adjustment. For instrument calibration in the middle and at the end of the range RS of the respective group are used. The main error of the instrument in the calibration points is determined, mainly, by the error of each of the groups, which should be understood to mean the error of the groups reproducing the values assigned to them. This error can be assessed through the error of verification of a group, preliminarily evaluated by accurate direct methods. Significant factors, determining this error, are the accuracy of the direct measurements, number of specimens, making up the group, and degree of their identity by the controlled parameter. The proposed procedure of statistical assessment was used with success during evaluation of RS with fatigue cracks in tubular specimens [45].

CONCLUSIONS

We developed a methodology of metrological support of eddy current flaw detection means using RS. In particular, a classification of RS with artificial defects is proposed and respective examples are given, which confirm the validity of the proposed classification. Given as an example are the designs of composite multi-valued RS for simulation of the surface and subsurface defects in the cylindrical and flat TO. Also presented is the design of a composite RS and the respective set of RS simulating the subsurface crack of the same size with four values of its location depth, and the respective signals of double differentiation ECP are studied experimentally. A method to produce RS for simulation of inclined cracks is proposed. A range of works are analyzed, which consider the possible causes for the difference in ECP signals from a natural crack and AD. Calculations by the method of volume integral equations were used to show that the main cause for the difference in ECP signals from the natural fatigue defects and AD is their width (opening). The influence of crack length on the features of the signal from parametric type ECP is considered, which should be taken into account during selection of RS parameters as regards crack length. A statistically substantiated method of valid evaluation of the parameters of RS with natural defects is presented, which was successfully used to assess tubular specimens with fatigue cracks.

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