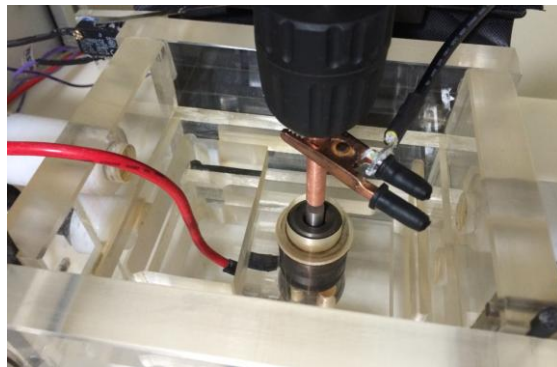


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SYNTHESIS AND DESIGN OF HYPERBOLOID GEAR DRIVES: METHODOLOGY AND ASPECTS

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Abstract: *The high current requirements for the characteristics determining the accuracy, reliability and efficient manufacturing of modern machines, apparatus and devices applicable in various fields of industry and transport in a big extend dictate the applied scientific methodology to the technological synthesis, design and production of gears. In the processes of synthesis and design of the different types of gear transmissions, the designer faces an extremely complex set of questions to solve, which together define the desired optimal construction. In this case, an optimal design means a gear transmission that is capable of delivering preliminary defined kinematic and / or strength requirements at minimum design, production and operation costs (including the repair costs during their exploitation).*

This work presents a review of the methodology, developed by the authors, oriented towards the synthesis and design of spatial gear mechanisms (hyperboloid gear drives), realizing rotations transformation between crossed shafts. The main principles, on which the construction of adequate software programs are based for the synthesis of treated transmissions, are presented.

Keywords: HYPERBOLOID GEAR DRIVES, SPIROID AND HELICON GEARS, SYNTHESIS, DESIGN, MATHEMATICAL MODEL, COMPUTER PROGRAMS

1. Introduction

The high current requirements to the accuracy and reliability characteristics of the machines, apparatus and devices applicable in industry and transport in a big extend dictate the applied scientific methodology to the technological synthesis, design and manufacture of gear drives. In the processes of synthesis and design of the various types of gear transmissions, the designer faces an extremely complex set of questions to solve, which together define the desired optimal construction. In this case, an optimal design means a gear transmission that is capable of delivering the preliminary defined kinematic and / or strength requirements at minimum design, production and operation costs (including the repair costs during their exploitation. By its essence, the systems of requirements for different quality characteristics of the gear drives, ensuring its optimality, are [1]:

- **geometric ones**, which control the kinematic exactness, smoothness of the work process, the character of the contact (the placement of the contact point, an orientation of the contact lines in the contact points) in the relation of the gear drives' loading capacity and etc.;
- **dynamics ones**, that influences the noise and vibrations in the gear systems, the conditions for occurring the resonance phenomena and etc.;
- **strength ones**, determining durability and reliability of gear drives, including the transfer of nominal power in the process of rotations transformation with avoidance of "scratching" (scoring), "pitting" and etc. on the active tooth surfaces of the synthesized mechanism;
- **economic ones**, defining the production costs (e.g., per unit of power), energy loss in motions transformation (coefficient of efficiency) and etc.

Considering the wide variety of requirements to the quality characteristics of the gear drives, in connection with the actual existing technological, manufacturing and economical price limitations, it is obvious that the solution of a real task of creating an optimal gear design is realized with some approximation with respect to the theoretical variant. The realization of this only possible approach to creating real gear drives requires it to be complex one, which should be foreseen in the processes of synthesis and design of the gear systems.

2. Aspects of Computer Design

The wide variety of gear mechanisms used in industry and transport, as well as the permanent pursuit of researchers to create new and improved gears drives on one hand and on the other- the different and changing approaches to the mathematical modeling for

synthesis and design, make it difficult to realize universal CAD systems. In connection to all said above, it specially should be noted the note the extremely dynamic development of modern technical computing tools and software programs. This often requires a reassessment not only of the way in which computer programs are organized, but also leads to informal changes of applied mathematical models [2]. In order to realize these researches into the field of theory gearing, as well as to provide an adequate scientific support for this type of production, the computer design has evolved, forming three types of software:

First type. The programs, included here, are designed to study the mutual influence between various kinematic, structural, technological and exploitation parameters of the studied gear drives. Essentially, this type of software is not subordinate to a particular strategy associated with the construction of CAD systems. The elaborated mathematical models, algorithms and computer programs are designed to determine the influence of one or other real-life existing parameters on the qualitative characteristics of the concrete gearings. However, the programs created in this case can be used as software modules, which are elements of system of criteria for the quality control of the synthesized gear drives.

Second type. This group includes computer programs organized on the basis of algorithms, contained in standardization documents [3], company methodologies [4] or handbooks (guides) [5-8]. Here, it should be included, the program products, elaborated on the basis of algorithms for geometric and strength calculation of the traditional types of gear drives: cylindrical involute with external and internal mating gears, cylindrical worm gears, bevel gears with straight teeth and so on. It should be noted, in particular, that the algorithms used in the prevailing number of cases do not ensure the optimization in the synthesis and design of gear transmissions. For example, the known algorithms for the synthesis of cylindrical involute, conic and worm gears [6] are able to provide only the technological and instrumental requirements for their manufacture, in terms of standardized determined modules (ptiches) and in terms of the occurrence of undercutting on the tooth surfaces under instrumental gearing or interference - in work gearing. Secondly, this category of software products it can also be included those, through which the strength characteristics of the already geometrically and technologically synthesized gear drives [3] are examined. As such, these computer programs can be treated as tools for analysis of the gear mechanisms.

Third type. Included in this category of computer program products are those based on mathematical models, developed on the basis of the specially oriented scientific studies. For example, for Bulgaria, these are the computer programs that covers the synthesis and design of Spiroid and Helicon gear sets (Spiroid and Helicon

are registered trade mark of Illinois Tool Works, Chicago, Illinois) [1, 9, 11], and with conic and hypoid gear mechanism – type Gleason [5, 12, 13]; and others. For the contemporary gear transmissions, including even classical gear mechanisms, treated in terms of current engineering requirements, the elaboration of new mathematical approaches to their geometric, technological and strength synthesis is required. The process of optimization synthesis, in this case, is realized by applying the **method of direct search**. This method provides an opportunity to reduce the number of calculated gear pairs, which compose the synthesized gear mechanism. It will be reminded, that the essence of this method is as follows:

- input parameters are defined, as well as those that will not be changed throughout the whole synthesis process;
- the variables parameters are determined as well the way of their variation, respectively;
- the process of varying the defined variable input parameters compared to their initially given value continues, until the preliminary defined optimization criteria are fulfilled;
- from the calculated pairs of conjugated gear sets, a final variant is chosen for which, there is the best fulfillment of the additional conditions (restrictions) introduced in the mathematical model.

In other words, the process of optimization synthesis and design of the third type of software is based on adequate iterative procedures, by which the desired solution is found by variation of certain parameters.

3. Computer Programs: Principles and Methodology

The computer programs designed for the synthesis and design of linear contacting hyperboloid gear mechanisms belong to the third type software. Considering, the known methodological limitations [14], the following sequence is kept when constructing this type software, for elaboration of the system for the computer design of hyperboloid gears with linear contacting tooth surfaces.

3.1. Basic Principles and Approaches of the Mathematical Modeling for Synthesis and Design

When profiling the kinematically conjugated surfaces, by means of which the rotations transformation between crossed axes is realized, the basic observed principles are the principles of T. Olivier [1]. Here, it will be summarized only that part of them, which is directly related to the construction of the concrete computer programs.

When generating the tooth surfaces Σ_1 and Σ_2 , firmly connected with the bodies B_1 and B_2 , through the generating (instrumental) surface Σ_J , firmly connected with the body B_J , the mentioned bodies B_1 , B_2 and B_J realize rotations motion with different vectors of rotation. In this case, relative motions are characterized by velocity ratios $i_{12} = \omega_1/\omega_2$, $i_{iJ} = \omega_i/\omega_J$ ($i = 1, 2$). If the surfaces Σ_2 (or Σ_1) are respectively a one-parameter envelope of the instrumental surface Σ_J , when the conditions $\Sigma_J \equiv \Sigma_1$ ($\Sigma_J \equiv \Sigma_2$, respectively), $B_J \equiv B_1$ ($B_J \equiv B_2$, respectively) and $i_{12} = i_{J2}$ ($i_{12} = i_{J1}$, respectively) it is said that the tooth surfaces are generated in accordance with the second principle of T. Olivier. In this case, Σ_1 and Σ_2 have always a linear contact.

In [1, 14-17], are formulated two approaches (applied by the authors) to the elaboration of mathematical models for the synthesis: mathematical modeling, which defines and optimizes the geometric, technological and exploitation characteristics of the design gear drives in a small vicinity of the *pitch contact point* and

a mathematical modeling related to the ensuring of the quality characteristics in the whole *region of mesh*.

In connection with all said, it is obvious that the methodological difference between the two approaches for the synthesis of spatial gear drives requires to define in advance the adaptability of the future designed hyperboloid gear drive to one of the two mentioned approaches. The determination of the adaptability of the planned procedure for creating of an adequate mechano-mathematical model is a complex creative process, requiring the knowledge of both the theoretical content of the approaches to the synthesis and the specific technological and exploitation requirements characterizing the created transmissions.

3.2. Principles of Organizing the Design Process

The following principles are obvious and have been commented by various authors [1, 2, 9, 12-15]. Here, the focus will be put on those which are determining for the construction of the computer programs for synthesis of gears type Spiroid and Helicon.

Determination of the groups of independent and variable input parameters. To the group of independent input parameters a set of standardization modules should be included, that determines the technological capabilities of the hobbing machines; coefficients that define the tooth geometry as a function of the modules; coefficients of frictions between the different pairs of materials applicable for producing of the toothing of the conjugated gear pairs; coefficients, linear and angular values associated with the design of the instrumental equipment and etc.

To the input data parameters, among which the variable ones are chosen, as a rule are included those which define the overall geometry of the calculated gear system. Here belongs the parameters determining the dimensions of the gear structure: the offset, distances from the offset to the planes in which the pitch circles lie; the angles defining the orientation of the above said planes relative to the pitch normal and etc. The variable input data include also those, from which the geometry of the conjugated active tooth surfaces depends: the independent coordinates of the tooth surfaces; their helical parameters; parameters which determine face width of the teeth, etc.

Introducing the main analytical relations, which are based on the chosen approach to the mechano-mathematical modelling.

Here are included solutions of the fundamental tasks of the synthesis upon a pitch contact point and upon a mesh region with the application of the adequate geometric interpretations of the basic equation of meshing, namely [1, 14-17]: the task for the synthesis of pitch circles; the task for the defining the geometry of the active tooth surfaces by their linear and angular characteristics in the pitch contact point; the task for defining the singularity in the pitch contact point (without describing the analytical type of the tooth surfaces); the task for analytically defining of the entire mesh region; formulations of relations, which are used to determine the optimal dimensions and placement of the region of mesh on the active surface and etc.

This principle of organizing the computer design includes also the introduction of geometric and kinematic relations, intended for the reduction of the input parameter sets.

Constructing the complex process for synthesis and design of hyperboloid gear drives. This is realized by defining the separate sub-stages of the synthesis and design in their sequence and interconnection. This principle, applied in the design of each computer program, is directly dependent on the type of functioning, in the elaborated algorithm, complex of criteria. Those criteria determine the preliminary defined quality characteristics of the gear mechanism in dependence of the accepted approach to the mathematical modelling. A distinctive characteristic of the accepted principle for construction of the complex process for synthesis and design is the chosen approach for the estimation of the calculated option of gear drive.

4. Programs for Synthesis of Spiroid and Helicon Gear Drives

The shown considerations for designing of software programs, applicable to the synthesis of hyperboloid mechanisms are also realized in connection with constructing three types' software products for the design of Spiroid gears, which functional relations are shown in Fig. 1 [1]. Each one of the illustrated three main directions, has its own importance. It means that the user can restrict himself to use the results of only one program; to analyze and interpret these results and then after an adequate assessment, to go through the entire process shown in the figure.

Further below, each of the directions, that includes the whole process of synthesis and design of Spiroid gears, will be considered.

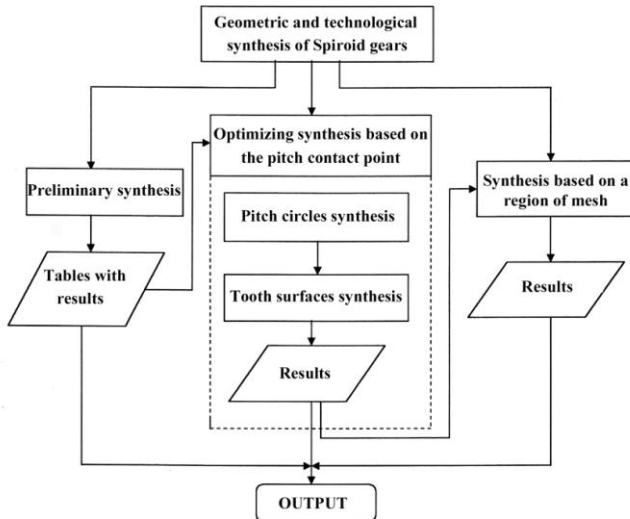


Fig. 1 General block-scheme of the approaches for the synthesis of Spiroid gears

4.1. A Software Program for a Preliminary Synthesis

The aim of the preliminary synthesis is to be calculated the main geometric parameters of the special case of Spiroid gear, when the angle, at which the rotations axes are crossed, is 90° , and pinion is of cylindrical form. With other words, the preliminary synthesis of the Spiroid gears is essentially oriented to the geometric dimensioning (without an optimization) of hyperboloid drive of type Helicon [11, 18].

The mathematical model upon a pitch contact point is in the basis of the program for a preliminary synthesis. It is assumed that this point is placed on the outside cylinder of the Helicon pinion [19].

The input data of the computer program are: gear (velocity) ratio u ; offset a_w ; Z_1 - number of teeth of the pinion depending on the degree of accuracy and the conjugation type of the tooth surfaces; a standard pinion tooth deflection (thinning) - Δb ; set of standard axle modules; coefficients and etc. In the commented program, the possibility of defining the following geometric-technological requirements is taken into consideration when choosing the outer diameter d_{a2} of the gear:

- in the case of the double bearing of the pinion, when one support is located in the field of the offset (in this case the synthesized gear drive is characterized by smaller sliding velocities [18]);
- to ensure the possibility of generating the gear sets, over a wide range of external diameter d_{a2} variations, and with the use of hobbing machines.

The program works for velocity (gear) ratios of up to 100 and offset not exceeding 250 mm. The only optimization ensured by this

program is related to the selection of a standard axle module of the Helicon pinion (the calculated axle module has to belong to the set of standard input modules).

The data for u , Z_1 , a_w , Δb and one of the mentioned geometric-technological conditions is input by the designer at the start of each computational procedure.

Thus, only by inputting the above mentioned input data by the designer, the program calculates and chooses the values of the standard axle module, outer and inner diameters of the pinion and the crown (gear), the width of the toothing of the gear and the length of the generated part of the pinion, the minimum mounting distance of the pinion and etc. The program enables a technological check of the values of the big profile angle of the teeth (corresponding to low-side driving) as well as for obtaining variations of the gear drive for the minimum and maximum possible values of the number of the teeth of the gear (crown).

The organization of the program for a preliminary synthesis is illustrated on Fig. 2 [1].

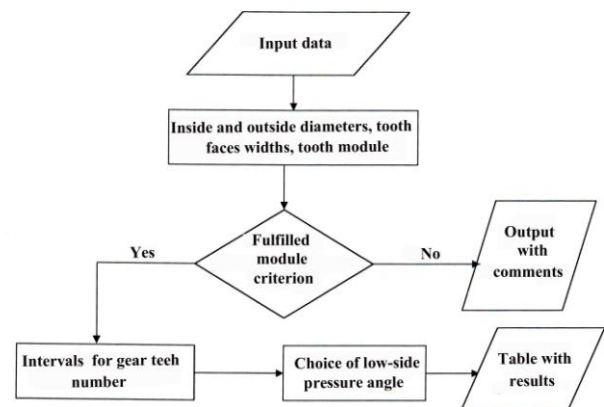


Fig. 2. Scheme of preliminary synthesis program

4.2 Program for Optimization Geometric and Technological Synthesis of Spiroid Gears upon a Pitch Contact Point

This program includes solving of the following tasks [1]:

- Synthesis of geometric pitch circles.
- Synthesis of the active tooth surfaces of the Spiroid pinion and of the cutting tool for generation of the Spiroid crown (Spiroid hob);
- Verification if that the accepted quality criteria of the gear drive are fulfilled.

From the formulation of the defined tasks, it can be seen that the algorithm of this program corresponds to the approach to mathematical modeling for synthesis upon a pitch contact point [1, 14-17]. In this sense, when designing the Spiroid gears, it is of particular importance to select the location of the pitch contact point in the fixed space. The placement of the pitch contact point (as a common point of the pitch circles and conjugated active tooth surfaces) affects on one hand on the common geometry of the designed gear system (overall dimensions of the gear pair) and on the other- on the geometry and proportions of the gears' teeth, as well as on the gears' quality (through the geometric, kinematic and strength characteristics of the conjugated gear pair).

For the purposes of this study, here will be briefly outlined some of the information contained in [1, 14-17], dealing with the geometric nature of the externally contacting geometric pitch circles.

The pair of the pitch circles ($H_1^c : H_2^c$) from the mentioned type are circles H_i^c ($i = 1, 2$), having only one contact point P . Their centers are places on the axes of rotations $i-i$ ($i = 1, 2$) of the movable links, and the corresponding circles are perpendicular to those axes. Mutual placement of the crossed axes is uniquely determined by the angle $\delta = \text{constant}$ between the skewed axes and by the length of their axis – the offset (center distance) $a_w = \text{constant}$. The position of the geometric circles H_i^c ($i = 1, 2$) in respect with the rotations axes $i-i$ ($i = 1, 2$) and with their offset line is defined by four parameters for each circle. The condition for the two circles to have a common contact point is expressed by five independent scalar equations. Hence, the mutual position of two circles is not defined in a unique way. It is a function of 5 independent parameters. The synthesis of geometric pitch circles is preceded by the decision, which five of the eight parameters (for both circles) to be chosen for independent ones and how to choose the intervals for their variation.

For this specific case, these five independent parameters are chosen as: an angle δ between the axes of rotations $i-i$ ($i = 1, 2$); the offset a_w ; the angle δ_1 , which is concluded between H_1^c and the pitch normal $m-m$ (half of the angle at the top of the pitch cone H_1^s of the Spiroid pinion); radius r_1 of H_1^c and the distance a_1 between the offset line of the gear drive and the plane in which H_1^c lies.

The ambiguity of the solution enables the possibility these free parameters to be discreetly changed within certain limits and among many pairs of geometric pitch circles to search for those ones, which parameters ensure that the preliminary defined requirements for the quality of the synthesized gear drives in the vicinity of the pitch contact point are satisfied. The criteria used in the program will be discussed further below.

The program allows choosing the type of conic linear helicoid, applied as active tooth surfaces of the Spiroid pinion: convolute, Archimedean or involute ones. The calculation of the necessary and sufficient geometric and technological parameters for the design of the Spiroid gear pair and cutting instruments are realized for the required type of conic helicoid.

The indicators, which serve to control the quality of the gearing, are essential for the design process. As it has already be mentioned, the dependence on the solution of the task for the synthesis of the pitch circles from concrete free parameters, should be searched among the optimal geometric, kinematic and technological quality characteristics in the vicinity of the pitch contact point. They will be briefly explained.

Basic technological criterion. This is the main criterion related to the technology of elaboration of Spiroid gears. It is related to the reduction of the nomenclature of cutting tools by ensuring the conditions for the design of Spiroid hobs with standard modules (hob parameters are functions of this module). This causes the requirement that the calculated in the pitch contact point module to coincide (with a given exactness) with any of the modules contained in the input set of standard modules.

Criterion controlling the singularity in the pitch contact point. The constructed criterion is analytically described in [1]. The ensuring of the implementation of this criterion helps to reduce the ordinary nodes from the mesh region of the synthesized gear drive. Hence, it leads to the improvement of its loading capacity, of the efficiency and of the durability. It will be reminded, that the elimination of the singularity of first order, by this criterion, is guaranteed in vicinity of the pitch contact point. The optimization,

when using this criterion, is realized by the verification of the analytical dependencies introduced for each of the selected combination of the five independent variables.

Criterion for controlling the transmission angle of the normal force (pressure angle). This criterion provides optimization of gear drive in terms of the transmission of the normal forces from the pinion to the big gear (crown), when the gear mechanism is operated under the conditions of the rotations transformation at low-side driving.

Criterion for controlling the value of the Spiroid pinion spiral angle. By this criterion is carried out the control of the value of the angle in the pitch contact point. Its values have to belong to definite intervals in accordance to the purpose of the designed gear drive.

Here, it should specially be noted, as it is shown in [6], that the choice of the appropriate values for the pressure angle and the Spiroid pinion spiral angle of the longitudinal line of the active tooth surface $\Sigma_1^{(1)}$ in the pitch contact point substantially affect the efficiency of the gear drives. Therefore, by appropriately selecting of the geometric characteristics of the tooth surfaces of the Spiroid pinion, an indirect control of the gear drives' efficiency is achieved. It also should be mentioned, that from the calculated equivalent variants of the synthesized gear mechanisms, from a geometric and technological view point, the program allows to select that one which has the highest value of the coefficient of efficiency for the computational (pitch) contact point.

Criterion related to the durability of the gear drive. It controls the magnitude of the sliding speed at the computational contact point, depending on the chosen material for the toothing of the Spiroid gear - different types of bronze.

Criterion controlling the hydrodynamic conditions of meshing. This optimization aims the accomplishment of the following condtions: the synthesized gear drive has to obtain a maximum as a value of the summed circumferential velocity $|\bar{V}_\Sigma|$ in the pitch contact point and a minimum value of the angle Ω , which $\bar{V}_\Sigma$ concludes with the normal to the contact line in the pitch contact point.

Technological criteria for hobbing. These criteria are related to the choice of the minimum value of the axial (normal) profile angle of the Spiroid hob, in order to provide optimal conditions for hobbing, both in terms of cutting the metal and in relation to the strength characteristics of the cutting elements of the hob and etc.

In number of design cases, some of the initially defined independent parameters could be fixed due to the specific requirements (or example because of requirements for the maximum sizes of the gear drives and the mutual position of the shafts of the gears), which results in reduction of the number of independent variables without limitation to search and find an optimal geometry of the tooth surfaces.

Input parameters of the software program: number of the Spiroid pinion' threads and number of Spiroid gears' spiral teeth; offset; standard pressure angle; type of the conical helicoids (type of the tooth surfaces of the Spiroid pinion); type of the bearing of the gear shafts (on two bearing supports or on a console); frequency of revolution and etc. Keys parameters will take values of 1 or 0 depending on whether a given criterion will be taken in consideration for the synthesis or not. For each of the free parameters, the minimum and maximum values as well as the pitches of variation, are chosen. The independent variation cycles in the computer program are equal to the number of the free parameters.

On Fig. 3 the main block-scheme of the commented above program can be seen. The table of the results consists of: the basic geometric parameters of the Spiroid pinion and of the Spiroid gear, the design parameters of the Spiroid hob, geometric and constructive parameters of the three-link spatial gear mechanism,

parameters related to the quality of meshing at the pitch contact point, such as coefficient of the efficiency of the gear drive, forces acting in the pitch contact point (pole of meshing); loading of the bearing supports, etc.

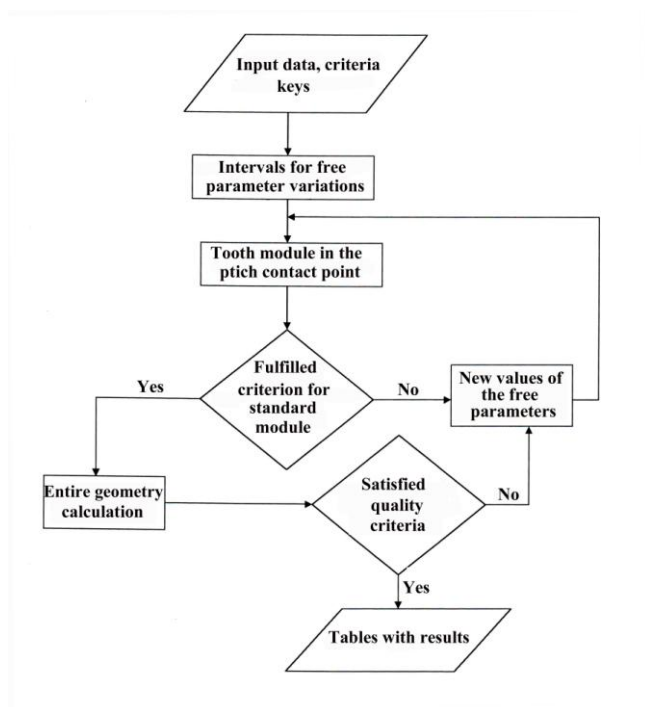


Fig. 3 Program scheme for an optimization synthesis of a Spiroid gear pair

It should be mentioned that, when the bearing supports are calculated, the distances between them and the pitch circles in real dimensions *mm* or dimensionless - as the ratio of the distances to the diameter of the pitch circle of the Spiroid gear are given. In the program, all forces, that act in the pitch contact point and at the bearing supports are dimensionless in relation to the peripheral force, acting on the Spiroid gear. If in the input of the program, the torque on the gear shaft or a torque on the pinion shaft is given, then this peripheral force has a concrete value and all forces and loads are calculated in [N]. Analogically, the sliding velocity is calculated as the ratio with the magnitude of the Spiroid pinion' angular velocity. If in the input, the numbers of pinion' revolutions per minute are given, then the sliding velocity is obtained in [*m/s*].

4.3. A Computer Program for Synthesis upon a Mesh Region

This program for synthesis of Spiroid gear, based on the commented in [1] mathematical model, represents a logical final stage of the organized complex process of the synthesis for this class high-reduction spatial gear mechanisms. This approach is applied in the following two cases:

When synthesizing a gear drive for which elaboration it has to be used the existing instrumental equipment (in particular an existing Spiroid (Helicon) hob).

In this case, in the designing of the gear drive, it is not possible to define an optimally positioned pitch contact point. In a number of cases, the existing instrumental equipment is suitable for generating the gear mechanism, for which it is not possible to define a pitch contact point in the mesh region. In this case, the constructively defined region of mesh is tested for the singularity of first and second order. In case, when the constructively defined gear drive contains an unacceptable amount of undercutting points and ordinary nodes, a change of the location of the mesh region in the fixed space is used.

When types of Spiroid (Helicon) reductor are synthesized. The type reducers represents a family of products, which are elaborated on the basis of the same: corpus details; gear blanks;

purchased groups of assembled details and parts. A rational and applied approach by the authors of this research is as follows:

At the beginning a basic model is designed, the synthesis of which is realized by using the computer program for synthesis upon a pitch contact point. The rest of the elements of the family of the created type are designed, by using adequate analytical dependencies [1], that ensure design of gear drives, so the ordinary nodes (contact points) are completely eliminated from their mesh region. Thus, the selected types of gear set, together with the base gear drives, are tested for the presence of singularity of second order in the whole region of mesh.

Through the created software program for the synthesis upon a mesh region, the entire region of mesh is checked in order to determine the type and amount of singularity. For the discrete variation of the meshing parameter φ_1 (an angle of rotation of the Spiroid pinion), the contact lines on the active tooth surfaces $\Sigma_1^{(j)}$ of the pinion are defined as a function of one of their curvilinear coordinates $u^{(j)}$, $g^{(j)}$. The parameter φ_1 varies in the interval $k\pi$, as the real number k depends on the geometric-kinematic characteristics of the synthesized gear drive, as well as from the foals of the study. The curvilinear coordinate $g^{(j)}$ varies in an interval, which depends on the length of the generated part of the pinion - L_1 and its axial module m , i.e. $g^{(j)} \in [-L_1/m, +L_1/m]$. The interval is divided by the number of points chosen by the designer. For each of these values, it is firstly checked whether the curvilinear coordinates belong to the mesh region, and then checking if that these curvilinear coordinates satisfy the analytical dependencies that indicate the presence of ordinary nodes and undercutting points. The finding is noted with the relevant text in the software program.

The input date in the program are [1]: number of teeth of the Spiroid pinion Z_1 , number of teeth of the Spiroid crown Z_2 , offset a_w , a distance from the offset line to the origin of the coordinate system $S_p(O_p, x_p, y_p, z_p)$, in which the equations of conic linear helicoids, profile angle, the length of the generated part of the Spiroid pinion, the module of the tooth surfaces are written. These data can be obtained from the synthesis of the base model upon a pitch contact point. In this case after the check with the program for synthesis upon a mesh region, the base gear drive is synthesized upon the so-called **combined approach**. The input of the program can be set from the constructive considerations, depending on the available instrumental and technological equipment. In this case, the synthesis upon mesh region is transformed into evaluating of the constructively chosen parameters.

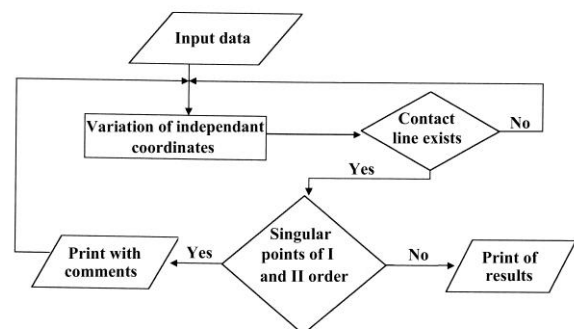


Fig. 4. Computer program for synthesis upon mesh region

The computer program is organized upon following Fig. 4 [1]. In the appendices to the publication [14], exemplary calculation

results are presented from the execution of the computer programs for synthesis of Spiroid gear sets.

5. Conclusion

The current work presents an adequate review of the created methodology and the approaches to the synthesis and design of hyperboloid gear mechanisms with face mated gears. It is an actualized and added presentation of the illustrated in [20] strategy for synthesis of gear drives with crossed axes.

The main features of its content are as follows:

- A classification of the types of specialized software applicable in the analysis, synthesis and calculation of gear drives is realized.
- The principles, applied by the authors, for organization of the process of the synthesis and design of hyperboloid gear mechanisms, are briefly defined (described).
- The essence of the elaborated computer programs for preliminary synthesis, optimization synthesis upon a pitch contact point and upon a region of mesh, applicable in the design of Spiroid and Helicon gears, are summarized.

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PROCESSING OF BIMETALS IN THE ELECTROLYTE PLASMA

ОБРАБОТКА БИМЕТАЛЛОВ В ЭЛЕКТРОЛИТНОЙ ПЛАЗМЕ

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Abstract: Electrolyte plasma processing is environment-friendly and high-effective method to treat surfaces of metals and alloys and can be used for heat or thermochemical treatment as well as for cleaning or polishing of metal surfaces. Modes of processes in the electrolytic cell for different metals can partially overlap. So it is possible to perform the same or different processing for different metals (including components of bimetal) simultaneously. This article describes modes to be established at the active electrode during the anodic process, and application of these modes to various types of treatment of bimetals. It is shown that there exists an option of separate or simultaneous heat or thermochemical treatment, as well as polishing of one or both surfaces of bimetals.

KEYWORDS: BIMETAL, ELECTROLYTE PLASMA, HEAT TREATMENT, POLISHING.

1. Introduction.

Bimetals are modern composite material, including several (usually two) metallic layers jointed by adhesion or chemical bonding. Practically all industries use bimetals due to their unique complex of functional characteristics, which are not inherent to components. For example, bimetals can have high corrosion resistance combined with high strength and manufacturability or with high heat strength, electrical and heat conductivity.

Usually the jointing is the final procedure of the bimetals manufacturing. However, there are cases, in which it is necessary to produce heat or thermochemical treatment of one component without changing of properties of another. In other cases, it is required to polish both the surfaces of the bimetal.

There exist a lot of methods for heat or thermochemical treatment of metals, in which the entire material is subject to heating. In these cases, a localization of the thermochemical action is carried out by protecting the non-machined areas of the part surface by galvanic tinning, coppering, nickeling or by applying various pastes and coatings (e.g. [1]). However, these methods are not usually applicable for bimetals due to undesirable changes of mechanical or other functional properties of the second component, which are resulted from the heating due to the heat conductivity. Similar phenomena are observed during heating of separated areas of large-sized products by gas burners or by high-frequency currents [2]. In addition, it is not possible to process surface areas having a complex configuration by these methods.

Other problems arise during polishing of the surface of bimetallic products, since there are differences in the physicochemical and mechanical properties of each of the bimetal surfaces. The most popular methods of the metal polishing are [3]: mechanical or abrasive polishing; chemical polishing; electrochemical or galvanic polishing. Unfortunately, these methods have such drawbacks that do not allow (or significantly complicate) the polishing of the bimetals surface.

Mechanical properties of the bimetal components are usually strongly different and thus their simultaneous abrasive polishing is impossible. For example, the polishing of non-ferrous metals is usually much simpler (and thus quicker) operation than the polishing of steels. Chemical and galvanic polishing differs by the reagent or electrolyte compositions for various metals and alloys. For example, the electrolyte for Al polishing usually includes H_3PO_4 and H_2SO_4 , for Cu and carbon steel – H_3PO_4 and CrO_3 ; for stainless steel – H_3PO_4 with a little addition of H_2SO_4 . Besides that, electrolytes may include other additions. It is also important that the used reagents are ecologically hazardous and difficultly recycled.

These problems can be solved by the electrolyte plasma processing (EPP) of bimetals at anodic process (AP) [4-6].

Processes in the electrolytic cell at the active anode can be divided onto five modes depending on electric parameters [7]. These modes are: 1 – low voltage electrolysis (classical

electrochemistry) (LVE) – $0... (15\div 25)$ V; 2 – switch mode (Wehnelt's breaker) (SM) – $(15\div 25) ... (70\div 100)$ V; heating mode (HM) – $(70\div 100) ... (180\div 290)$ V; electro-hydro-dynamic mode (EHDM) – $(180\div 290) ... (300\div 360)$ V; contact electric discharges mode (CEDM) – higher $(300\div 360)$ V. Real values of the modes voltage boundaries depend on the metal and composition of the electrolyte.

Each of these modes can be used to treat surface of metals. The LVE results to anodic dissolution of the metal surface according to Faraday's law. A current output during this mode is depending on the metal type and varies from $15\div 20$ % for W to $95\div 98$ % for Cu [3]. This mode is used in various industries for polishing, deburring, etc.

The SM stimulates rapid dissolution of the active electrode both by pulse discharges and by intensive chemical reactions in a gas-vapor shell [8]. This mode can be used to produce needle-like tips from hard-to-process materials such as W, Mo, Ir, etc. or chemical compounds.

The anode specific erosion during the HM or EHDM of the AP can be significant [4, 6]. In these modes there are narrow ranges of the voltages with the maximal dissolution rate. And the current output is much higher than that during the LVE. Besides that, the classical electrochemistry distinguishes insoluble (inert) electrodes (Pt, Ir, graphite) and soluble ones, but after the plasma shell formation this difference is not actual. Particularities of the electrolyte plasma influence on the active electrode surface provide ability to treat metals in such electrolytes where they don't dissolve during LVE or where the current output is very little. These processes are used to polish metals in the electrolyte plasma [4, 5, 9].

The water solutions of salts are usually using to polish metals by EPP. For example, we have used water solution of fluoride and citrate of ammonium at the electrolyte temperature of $60\div 90^\circ\text{C}$ to polish Ti or Ag [10].

2. Experiments

EPP of bimetals were carried out during AP using experimental equipment described in [11]. Water-cooling bath was 2 l in volume. Second electrode (cathode) was made from lead or stainless steel. Cell voltage and current was varied in the ranges of $0\div 450$ V and $0\div 50$ A correspondingly. We used aqueous solutions with specific conductivity higher than $5\text{ Ohm}^{-1}\cdot\text{m}^{-1}$. The oxidation duration was varied from tens of seconds to 10 minutes. The electrolyte temperature was varied from 15 to 30°C for heat and thermochemical treatment and from 60 to 90°C for polishing. The rate of immersion of the anode into the electrolyte in all cases did not exceed 10 mm/s . After processing, the samples were washed by distilled water. The current density at the active electrode at the HM was $6\div 10\text{ kA/m}^2$ and at the EHDM $2\div 5\text{ kA/m}^2$, the temperature of the active electrode at EHDM is $90\text{--}100^\circ\text{C}$. The electrolyte temperature was measured by Hg thermometer. The active electrode

temperature at the heating mode was measured by "Testo 845" optical pyrometer. Morphology of the surface was studied by optical microscope Zeiss AxioScope A1. A reflection coefficient was measured using red laser light.

We have studied plated bimetal samples of various types produced by rolling with the layer thickness of 0.5...3 mm.

3. Results and discussion

3.1. Heat treatment of one component of bimetals at the heating mode of the anodic process

The HM of the AP is established when the gas-vapor shell completely covers the active electrode and the current density decreases to 10 A/m². This mode is used to heat the metal up to 400...1000°C. Followed EHDM is characterized by an increase of the gas-vapor shell thickness, intensive corona discharge, decreasing of the current density lower than 5 kA/m² and absence of high-temperature heating (the active electrode temperature is not higher than 100°C).

It is possible to choose the parameters for the AP to provide the HM on the surface of one component of bimetal (its temperature can be higher than 800°C) and the EHDM on the surface of the second component (it's temperature can be equal or less than 100°C). Thus, the heating of the bimetal will be selective. It is important that erosion will not appear on both the surfaces.

One example of such treatment is given by the following. We have studied the treatment of bimetal plate of steel AISI 321 and Al-based alloy 6063. Direct voltage electrolytic cell included bimetallic anode and lead cathode. The electrolyte was ammonium chloride water solution with specific electric conductivity of 34 Ohm⁻¹·m⁻¹ and the surface tension coefficient of 76 mN/m at temperature of 22°C. When the working voltage of 180 V was reached, the bimetallic electrode was immersed into the electrolyte. On the steel part of the anode, the HM was realized, and it's temperature was equal to 720°C. On the aluminum part of the anode, the EHDM was realized, and it's temperature was equal to 90°C. Cooling of the bimetal after the treatment was carrying out by turning off the current. Addition of corresponding reagents to the electrolyte [4] can provide nitration, carburization or carbonitration of the steel part of the bimetal.

Other bimetals were treated analogously. Modes and achieved temperatures are given in Table 1.

The use of this method to treat bimetals in electrolyte plasma allows the heat or thermochemical treatment of one metal to be carried out without heating the second metal above 100°C, and thus increases the quality of the processed bimetals and improves the manufacturability of the technological processes (the workpiece can have any configuration).

3.2. Polishing of bimetals at the electro-hydro-dynamic mode of the anodic process

EPP is the method to finishing conductive materials. This processing allows to remove the scale, to prepare the surface before covering by thin films and coatings [4, 5], to polish difficult profile surfaces of critical parts, to remove burrs, to blunten sharp edges and to produce decorative polishing of metal products. The EPP is largely devoid of the drawbacks inherent in mechanical and electrochemical polishing. Its advantages, in comparison with other methods of polishing, are high productivity and efficiency,

environmental cleanliness, high quality and rate of performed operations, as well as comparatively low cost.

To polish simultaneously surface of all bimetal product, it is necessary that EHDM was established at all surface. The voltage for EHDM establishing depends on the processed metal type and such molecular properties of the electrolyte as the surface tension coefficient and the kinematic viscosity: the greater these parameters, the lower the voltage, when this mode is set [4, 9].

The main characteristics of polishing quality are roughness and reflect ability. These characteristics depend from the chemical composition of processed material, voltage and duration of the EPP. The composition of processed material also determines composition and concentration of the electrolyte. Besides that, in some cases addition of such matters as glycerin, acetone, thrietanolamin, trilon-B, etc., which significantly influence on both coefficient of surface tension and kinematic viscosity of the electrolyte, can be used. These additions change conditions of gas-vapor shell formation and shift volt-ampere range of the EHDM [4].

The most important parameter which determines the polishing quality is working voltage. It was experimentally shown that when the voltage value decreases below a certain limit, the polishing quality significantly decreases. These minimal limits are: 220 V for stainless steels, 260 V for copper and copper-based alloys, 270...290 V for aluminum and its alloys, 280...290 V for argentine [4, 6]. However, an increase of the voltage over 360 V is unacceptable not only through economic reasons but through technologic ones. This increase can result in transition to CEDM of AP when the gas-vapor shell breaks down and the quality of the polished surface deteriorates [7].

The electrolyte temperature is one of the most important factors of the polishing quality. High quality of the polished surface can be achieved only if the electrolyte temperature is in 50...90°C range. When the latter is outside this interval, the surface quality is lower. Besides that, it should be borne in mind that electrolytes included ammonium salts, hydrochloric acid, some other components which can dissolve higher 85°C with formation of volatiles, and thus frequent adjustment of the solution composition will be necessary.

Electrolyte plasma polishing is usually carried out using water solutions of salts. For example, to polish Al or Al-based alloys, the water solution either of ammonium chloride or sodium chloride [5], or of potassium chloride, oxalic acid and glycerin [12] can be used, but, in order to polish stainless steels, the water solution of ammonium sulfate [13] can be used. So, processing schedules and electrolyte should be determined experimentally for each metal, alloy and especially bimetal or composite.

In this work we used to type of the steel/Al-based alloy bimetals. The first type consists of austenitic stainless steel AISI 321 and aluminum-based alloy 6063, the second type was made with austenitic stainless steel AISI 304 and aluminum-based alloy A92017. To polish above mentioned bimetals we used water solution including 2...6 mass % of potassium chloride, 1...4 mass % of oxalic acid and 1...2 mass % of glycerin. The voltage on the electrolytic cell was 320 V. We saw that in initial rolled state the both surfaces were frosted (Fig. 1) and the reflection coefficient was very small (0.5...2 %) (Fig. 2). The polishing during 2 min results in significant decrease of roughness (see Fig. 1) and the reflection coefficient increases up to 28 % for stainless steel and up to 21 % for aluminum alloy (see Fig. 2). Rapid decrease of the roughness is highly likely resulted from an active local

Table 1. Parameters of the EPP of bimetals.

Bimetal	Heated metal	Temperature in area of HM, °C	Temperature in area of EHDM, °C	Voltage between electrodes, V	Composition of the water-based electrolyte, mass %
Titanium / steel	Steel	620	80	300	10% NH ₄ Cl
Molibdenum / steel	Steel	630	90	300	15% NH ₄ Cl
Aluminum / steel	Steel	720	90	180	15% NH ₄ Cl
Aluminum / steel	Steel	850	90	220	15% NH ₄ Cl
Aluminum / brass	Brass	850	90	210	10%Na ₂ WO ₄ ·2H ₂ O

smoothing of the micro-relief in the places of the largest protrusions. Subsequent increase of the polishing duration results in a slower decrease in the roughness and an increase in the specular luster up to 41...42 % (see Fig. 2).

Obviously, it is easier to choose the electrolyte composition and technological parameters for polishing of metals than of bimetals. In this regard, for bimetals it is possible to achieve a greater reflection coefficient. For example, for parts made of aluminum alloy only, the reflection coefficient reaches 0.8 [4]. Thus, new additional studies are needed.

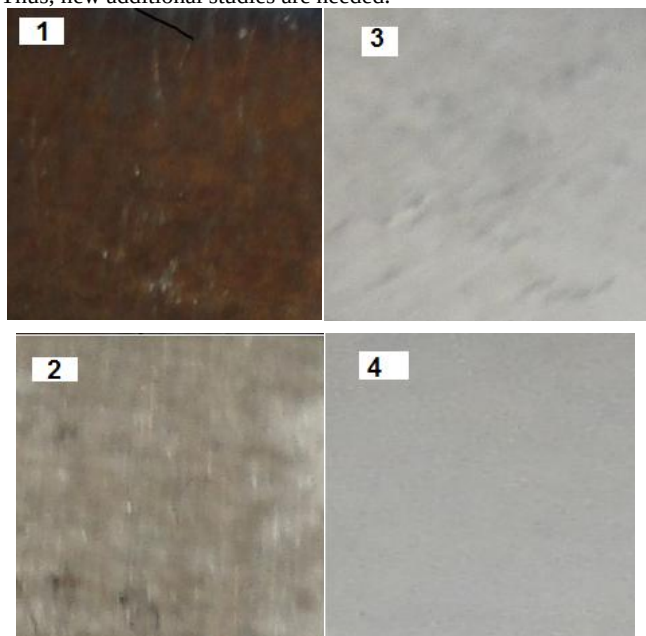


Figure 1. The surfaces of bimetal stainless steel AISI 321 (1, 3) / aluminum-based alloy 6063 (2, 4) before (1, 2) and after (3, 4) the polishing, respectively.

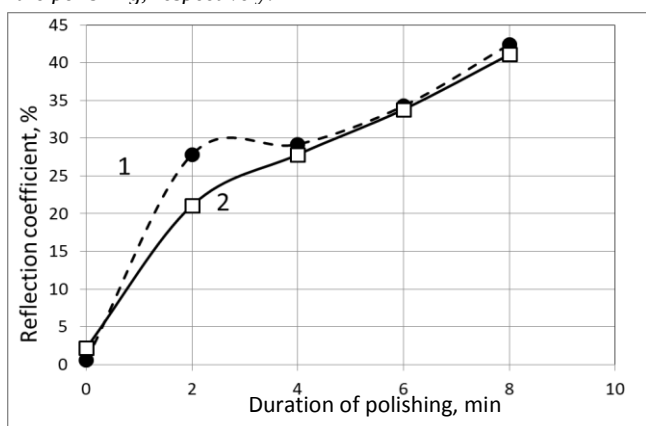


Figure 2. An influence of duration of the polishing on the reflection coefficient for bimetal stainless steel AISI 304 (1) / aluminum-based alloy A92017 (2)

4. Conclusions

1. This work shows possibility to carry out heat or thermochemical treatment of one component of a bimetal without heating of the second component over 100°C using electrolyte plasma processing. Treated bimetallic product may be of any configuration.

2. This work shows possibility of simultaneous electrolyte plasma polishing of both components of the bimetals, in particular bimetal of stainless steel and aluminum-based alloy. For this bimetal, polishing with 2 min duration significantly decreases the roughness and increases the reflection coefficient from less 2 % to more 20 % for both components. Subsequent increase of the polishing duration results to a slower decrease in the roughness and an increase in the specular luster over 40 %.

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DEVELOPMENT AND RESEARCH OF CHARACTERISTICS OF TWO-LAYER DIAMOND PLATES FOR DRILLING TOOLS

РАЗРАБОТКА И ИССЛЕДОВАНИЯ ХАРАКТЕРИСТИК ДВУХСЛОЙНЫХ АЛМАЗНЫХ ПЛАСТИН ДЛЯ БУРОВОГО ИНСТРУМЕНТА

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Abstract: Two-layer diamond-hard alloy plate is the cutting element of the drill bit and consists of a layer of polycrystalline diamond compact (PDC) bonded with the superhard alloy substrate (WC-Co).

In PDC cutter developed in FSBI TISNCM the plate of PDC, 2-3 mm thick and up to 18 mm in diameter, is bonded with a substrate of WC-Co, forming the working element of the drill bit. PDC consists of a diamond frame with grains of 20-10 microns impregnated with a binder metal Co. The ratio of the diamond fraction and the binder metal, as well as the size of the diamond grains vary, depending on the specifications. The entire PDC cutter is manufactured using high pressure and high temperature technology. The surface of the PDC plate is ground and polished to the required values.

Full-scale tests of PDC cutters showed that their impact strength and wear resistance are determined by the quality of the contact layer between the PDC and the substrate.

The paper presents the results of the study of the mechanical characteristics of PDC cutters, as well as the microstructure, element and phase composition and defects of the contact layer of PDC with substrate.

KEYWORDS: SUPERHARD MATERIALS, POLYCRYSTALLINE DIAMOND COMPACT (PDS), PDS CUTTER, PDS MILLING DRILL BIT, ACOUSTIC MICROSCOPY, INTERFACE PROPERTIES

1. Introduction

Superhard materials [1] are widely used in processing tools, among them the most well-known are Polycrystalline Diamond Compact (PDC) and Polycrystalline cubic Boron Nitride (PcBN). PcBN tools are mainly used for the treatment of iron-based hard alloys, while PDC are more commonly used for the treatment of highly abrasive non-ferrous alloys and composites.

It is known that polycrystalline synthetic diamond (such as "Carbonado") belongs to the hardest material known to man. Its characteristics are close, and, in some cases, exceed the characteristics of a single diamond crystal, which is 10 times harder than steel, 2 times harder and 10 times more resistant to wear than tungsten carbide. In this case, the polycrystalline diamond is 20 times stronger in compression than granite, while having the lowest coefficient of friction and the highest thermal conductivity of all known materials.

PDC tools are now actively used in the drilling of mineral resources for the search and production of hydrocarbons [2]. The basic tool of drilling equipment is the milling bit of rotary drilling (Fig. 1, a), the cutting elements (Fig. 1, b) of which move along the bottom of the well and cut the rock.

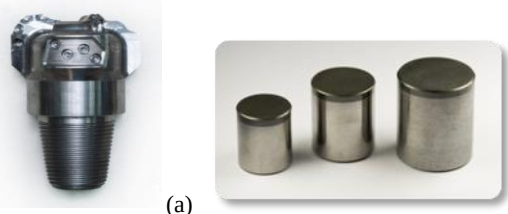


Figure 1. The working part of the milling drill bit (a) and PDC cutters (b)

Although the cost of bits equipped with PDC-cutters is a few percent of the total cost of the well, the drilling speed, the number of flights and the maximum length of well penetration, which determine the economic indicators of well development, depend on the quality of the cutting arms of the bits and their wear resistance.

The improvement of the cutting elements of drill bits and service mechanisms improve stabilization of motion and reduce the vibration of the drill bit to facilitate rapid and efficient drilling.

The energy of rock drilling is determined by the necessary destructive effect. Of all the major rock failure mechanisms, cutting is more efficient because rock tensile strength is less than compressive strength [3].

2. PDC-cutters made in TISNCM

PDC drill bit is a modern high-performance drilling tool for rotary drilling. PDC bits are drilled faster by cutting and consume less energy than rock chisels. The body of the diamond drill bit is equipped with PDC cutters, which destroy the rock cutting action, which is most effective when drilling hard stone. PDC cutters are developed and manufactured using the latest technology for drilling water, oil and gas wells or geothermal wells. They are a multi-component system, which includes: a) the diamond grains themselves, b) the binding phases used in the sintering process of the cutting PDC-elements and c) the method of connecting the diamond elements with the tool body. All elements require high-quality performance. Cutting elements are subject to severe abrasive-erosion wear conditions, causing heating to a high temperature. Not only the wear resistance of the PDC composite is crucial for the functional quality of the tool, but its thermal stability, thermal conductivity, impact resistance, thermal fatigue, strength and fracture toughness are equally important [3]. These properties determine the suitability of the diamond composite tool for the mining industry.

PDC cutter consist of diamond crystal grains, fused together with the participation of a metal "catalyst", which is usually cobalt. It also binds the PDC plate to the tungsten carbide substrate. Without cobalt, much higher pressures and temperatures would have to be applied to form a PDC compact, which today can not be applied in the field of mass production. However, the presence of cobalt in PDC cutters creates a problem when they are heated by intense abrasive friction during bit operation. First, the cobalt

expands much more than the diamond, and destroys the PDC. Secondly, when heated, cobalt graphitizes diamond [4].

In PDC cutters developed in FSBI TISNCM the plate of PDC, 2-3 mm thick and up to 18 mm in diameter, is bonded with a substrate of hard alloy, forming the working element of the drill bit. PDC consists of a diamond frame with grains of 20-10 microns impregnated with a binder metal. The ratio of the diamond fraction and the binder metal, as well as the size of the diamond grains vary, depending on the specifications. The PDC cutters are manufactured using high pressure and high temperature technology. The surface of the PDC plate is ground and polished to the required values.

Full-scale tests of PDC cutters in PDC bits have shown that their strength, wearability, and especially heat resistance, are determined by the quality of the contact layer (interface) between the PDC and the substrate.

The paper presents the results of the study of the mechanical characteristics of PDC cutters, as well as the microstructure, element and phase composition and defects of the contact layer of PDC.

Development of two-layer diamond plates is one of the tasks of creating in Russia a modern competitive on the world market of domestic production of tools for the manufacturing industry, oil and gas production and construction.

In 2017, at the Vyngapurovskoye field of Gazprom Neft in the Yamal-Nenets Autonomous district, pilot tests of the PDC bit with the first domestic polycrystalline diamond cutters were successfully carried out. A tool developed by the Samara company "Volgaburservis" and equipped with Russian cutters in the development and production of FSBI "TISNCM" designed to drill vertical, directional and horizontal wells in soft rocks with intercalations of medium-hard rocks. This corresponds to the conditions of construction of most of the wells in the November region of YANAO. The tests showed high wear resistance of the new equipment. The pilot section of the well with a length of 2237 m was passed without damage and loss of cutters, demonstrating good handling and high mechanical speed of penetration.

3. Studies of the interface characteristics of PDC cutters

We carried out a detailed study of the profiled interface on two samples of PDC cutters, as a non-destructive method of acoustic microscopy (AM), and on the plates 4 mm thick cut from the central part of PDC cutters. In the latter case, the phase composition of the boundary layer material (x-ray method), the microstructure and the defect of the layer (AM method) were determined; optical images of the interface section were obtained and the profilometry of vertical cuts of PDC cutters was carried out. Fig. 2 shows pictures of the whole PDC cutter (a) and cut vertically in the center of the sample (b).

The results of the studies showed that the characteristics of the two samples of PDC cutters differ slightly. So below are the data for one of the two studied samples of PDC cutters.

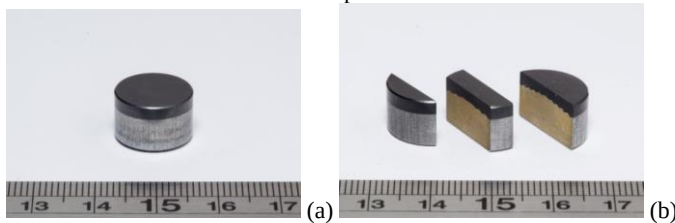


Figure 2. The whole PDC cutter (a) and with the cut out central part of the PDC cutter (b)

3.1. The study of the profiled boundary layer (interface) by means of acoustic microscopy

The principle of the acoustic microscopy is well known [5-6]. Acoustic microscopy is used to measure the local values of

ultrasonic velocities (microacoustic technique) and to visualize the bulk microstructure of a sample (scanning acoustic microscopy). The waveform of the reflected signal is an ultrasonic A-scan. 1D- or 2D- scanning of the probe beam over the specimen surface results in the raster-formation acoustic images (B- and C-scans, respectively). A SIAM Scanning impulse acoustic microscope (50 ÷ 200 MHz), designed and fabricated in the AM-laboratory of Emmanuel's Institute of Biochemical Physics, Russian Academy of Science, was used to make the measurements. Ultrashort probing ultrasonic 30-40 ns pulses were used for the measurements.

Figures below represent the A- B- and C-scans. Scanning of whole samples was carried out from the side of the diamond layer.

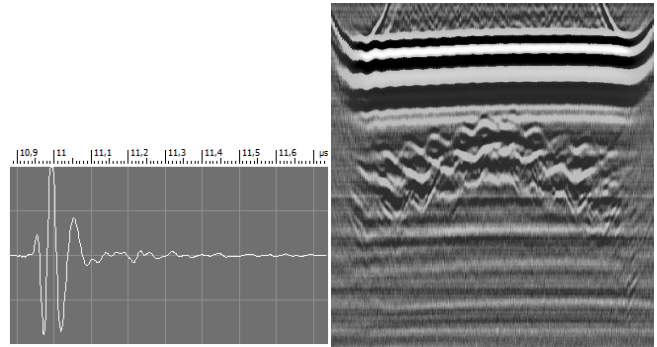


Figure 3. A- u B-scans of the sample No.1 PDC cutter

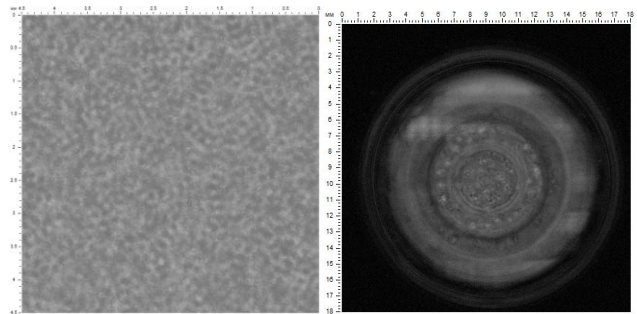


Figure 4. C-scans: subsurface microstructure of the diamond layer (C1) and the profiled interface (C2) of the sample PDC cutter

The C1-scan is obtained using parts of the A-scans array representing the reflected acoustic signals (100 MGz frequency echoes) from the subsurface layer of the sample. The C2-scan represents the 50 MGz echoes from the profiled interface of the diamond layer and substrate.

The AM images of the interface revealed the presence of defects in the form of pores, which are displayed on the AM images in the form of bright white dots. The study of the microstructure of the PDS cutters allowed to identify samples with the unsintered layer. An example of such a defect is shown in Fig. 5.

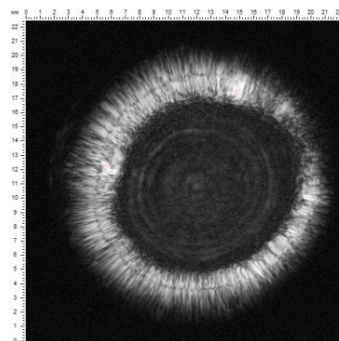


Figure 5. Sample of PDC cutter with defective (unsintered) cutting edge

4. Study of the PDC cutters vertical cuts

From the central part of the samples, plates with a thickness of 4 mm were cut using an electric spark machine (Fig.2). Cutting began from the PDC layer and was carried out at a constant speed. The cut surface was polished after cutting.

4.1. Optical images of cross section PDC cutters

Optical images with different magnification of sections of two PDC cutters are shown in Fig. 6 and Fig.7.

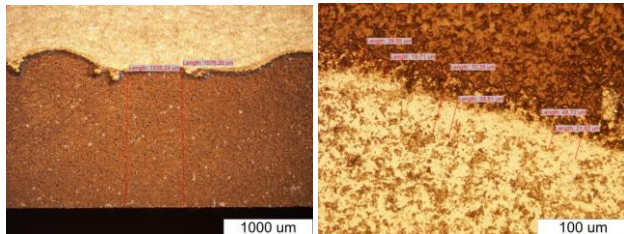


Figure 6. Sample №1. The thickness of the PDS layer in the center is 1.55 mm. The thickness of the interface is 44–75 μm.

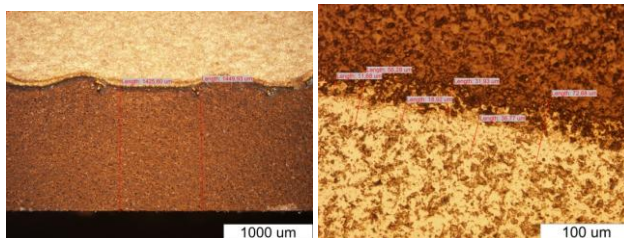


Figure 7. Sample №2. The thickness of the PDS layer in the center is 1.45 mm. The thickness of the interface is 50–70 μm.

Figures 6 and 7 show optical images of the interface in central part of the two PDC cutters. Optical studies have shown that the interface consists of two layers approximately equal thickness $\approx 35 \mu\text{m}$. Both samples on the interface show defects in the PDS layer, and their size in the sample number two is noticeably smaller.

4.2. Profilometry

Three-dimensional images of the surface were obtained using the optical profilometer Sneox (manufacturer Sensofar).

Three-dimensional images of the surface relief obtained by confocal optical profilometry. The method consists in obtaining a series of photos with a strong contrast in the focal plane of the measured sample and their cross-linking with depth reference. Images with high contrast and spatial resolution are obtained through the use of a point aperture limiting the flow of background scattered light emitted from the non-focal plane of the lens.

The size field of the obtained images $877 \times 660 \mu\text{m}$, resolution 1360×1024 .

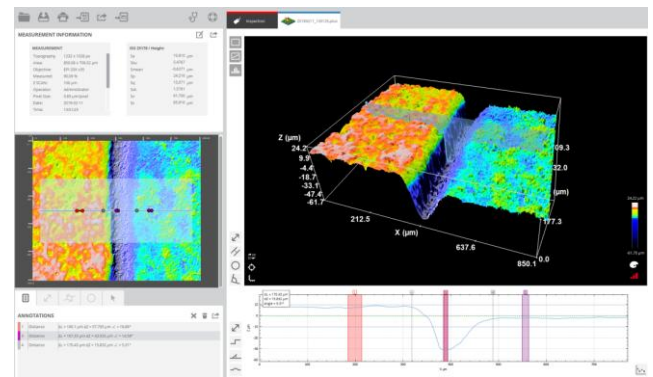


Figure 8. Profilometer images of cut surface directly after cutting

The profilometer image shows that the interface is represented as a groove with a depth of about $20 \mu\text{m}$ and a width of $140 \mu\text{m}$ (Fig.8). This is due to the fact that during electrospark cutting at a constant speed, the burning of the interface material occurs more intensively. It can be concluded that the interface has less strength than the diamond layer and the substrate.

The study of profilometry images after polishing the sample allowed to determine the thickness and depth of the interface. Figure 9 shows an example of one of the 10 profilometry drawings performed on two samples.

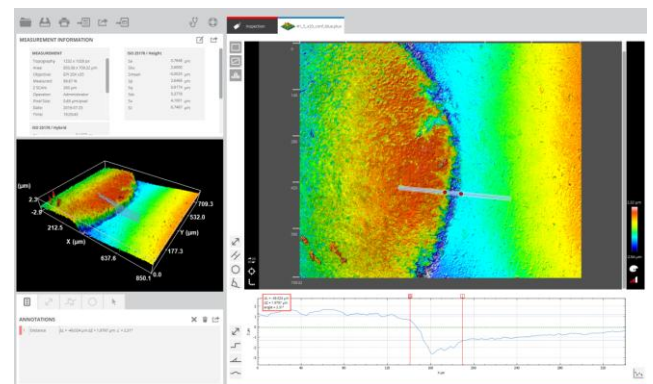


Figure 9. Profilometer images of cut surface after polishing

The study of the interface by the profilometry method found that the width of the boundary layer lies in the range from 49 to $25 \mu\text{m}$, and the depth from 2.0 to $1.1 \mu\text{m}$.

The profilometer images show defects in the form of a "weak" pore penetrating into the diamond layer. These defects are also visible on the AM images of both the full contact layer (the profile interface) and the vertical section of the PDC cutter (hereinafter).

4.3. AM image of the PDC cut

Figure 10 shows the AM image of the subsurface layer of two samples.

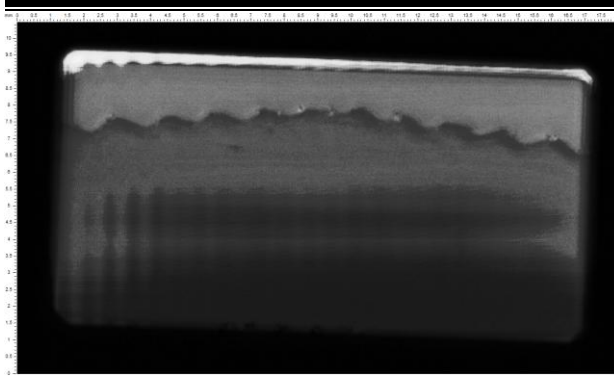


Figure 10. Cut of sample # 1. AM image of a subsurface layer 500 μm thick lying at a depth of 1 mm.

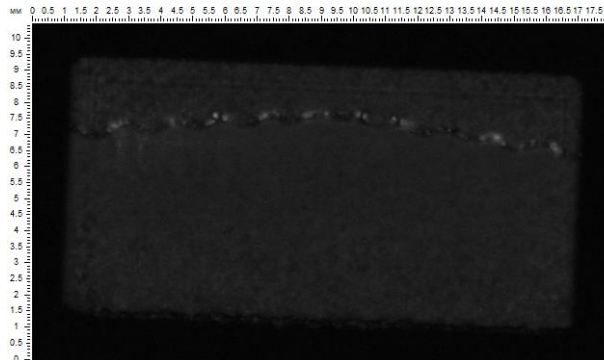


Figure 11. Cut of sample # 1. AM image of the subsurface layer 2 mm thick

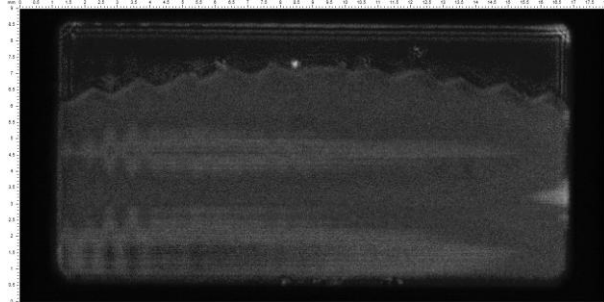


Figure 12. Cut of sample # 2. AM image of the subsurface layer 500 μm thick lying at a depth of $840 \pm 10 \mu\text{m}$.

5. Conclusion

The study of the interface of a two-layer PDC/WC-Co plate revealed the presence of defects in the PDC layer. These defects, as a rule, in the form of pores up to 50 μm in size, are visible both on the AM images of the whole interface and the slice, and on the images of profilometry. AM flaw detection interface of the whole PDC cutter will reject the PDC cutters before connecting them to the bit.

6. Acknowledgments

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7. Literature

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INVESTIGATION AND ANALYSIS OF ELECTROCHEMICAL MACHINING OF 321-STAINLESS STEEL BASED ON RESPONSE SURFACE METHODOLOGY

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Abstract: Electrochemical machining (ECM) is prevalent and competitive manufacturing process which uses for machining of hard and tough materials in high tech industries. Hence, experimental investigations on ECM of different materials play essential role to effectively utilize this process. This paper demonstrates a systematic approach for achieving comprehensive mathematical models in order to investigate the effect of machining parameters on the process responses of 321-Stainless-Steel and analysis of machining performance based on the response surface methodology (RSM). Machining voltage, tool feed rate, electrolyte flow rate and concentration of NaNO_3 solution were considered as the machining parameters while material removal rate (MRR) and surface roughness (R_a) were considered as the process responses. Experimental plan was performed by a central composite design (CCD), and the proposed mathematical models statistically have been evaluated by analysis of variance (ANOVA). Analysis shows that the RSM method has been appointed properly as the design of experiments (DOE) method for resolving curvature in ECM process responses. Also, the results show that the machining performance is greatly influenced by machining parameters. Especially the voltage and electrolyte concentration are the most important parameters.

Keywords: electrochemical machining, modeling, material removal rate, surface roughness, response surface methodology

1. Introduction

ECM is a modern and non-traditional machining which contributes significantly in various industries from consumer product to more sophisticated, high-tech applications and to produce micro to macro scale products. Moreover, ECM gives advantages over other conventional and non-conventional machining processes. As a case in point, conductive materials regardless of their hardness and toughness can be machined with a tool which is not harder than workpiece and there is especially no tool wear. In view of the fact that in this cold process there is no contact between cathode and anode, products without any residual stress and heat affected zone (HAZ) can be machined [1].

Even though traditional methods for conducting experiments such as trial-and-error, best-guest approach and one variable at a time (OVAT) still common [2], these methods are time consuming and incapable of detecting the interactions between variables [3]. Thus, implementation of design-of-experiments (DOE) method has increased in various manufacturing processes [4]. Response surface methodology, RMS, is capable of resolving curvature in the output associated with each input, detecting interactions effects and establishing mathematical models with suitable sets of experiments [5].

However, the ECM process involves several physical and chemical phenomena and a number of process parameters that make it difficult to model the process [6]. Consequently, experimental investigations, DOE, statistical and optimization approaches play a vital part in selection of proper selection of parameters setting which influence the machining performance considerably [7, 8].

There are researches that had been investigated this process experimentally and offer some excellent results and approaches for modeling and predicting machining conditions; still, much more experimental studies must be conducted to cover wide range of materials and methods for optimization and improving machining performance [9].

The purpose of this research is investigating the effect of ECM process parameters, i.e. machining voltage (x_1), tool feed rate (x_2), electrolyte flow rate (x_3) and electrolyte concentration (x_4) on machining criteria, i.e. MRR and R_a of 321stainless steel. This kind of steel contains titanium which making it an excellent choice for prolonged high temperature applications such as aircraft exhaust stacks, manifolds, welded equipment, jet engine parts and so on. Response surface methodology (RSM) is also used for correlating and analyzing the various machining parameters on the response;

therefore, mathematical models develop through RSM. In addition, the adequacy of the developed mathematical models has also been tested by the analysis of variance (ANOVA).

2. Experimental Procedure and Details

Set-up and machine:

The experiments were carried out on home-developed machine. This machine was set up in this investigation shows in Fig. 1 consists of four well-designed units, i.e. machine, electrolyte, control and power supply unit. The tool feeds forwards and backwards using the AC servo motor through a ground precision ballscrew with pitch of 2.5 mm and precision linear guides. Machining place was built by Plexiglas with a door provided more convenience for changing the workpiece. All used connectors, valves and hose made of 316 stainless steel, PVC and polyethylene; thus, the electrolyte composition does not change moving through these parts. Two PVC tanks have duty for supplying and storing electrolyte. Main pump with 3-ph AC motor and inverter provide setting electrolyte flow rate with help of ultrasonic flowmeter. Another magnetic pump used for draining electrolyte form storing tank to main supplying tank through filters. Output of power supply is 30 volt and 100 ampere.



Fig. 1 The ECM machine.

Materials and measurements:

Fig. 2 displays workpiece and tool with their fixtures in the machining chamber. Thirty-one 321stainless steel bars 8 mm in diameter specimens were used as workpiece for runs. Commercial cylindrical copper with the same diameter as workpiece were also employed as tool. As long as experiments conducted in stable conditions and with uniform initial gap distance, workpiece and tool were grinded and deburred to remove any possible surface irregularities to guarantee an even and parallel surfaces. The experiments were carried out in NaNO_3 solution electrolyte with various concentrations. The electrolyte flow system used in cross and planning method to ensure an effective flushing during machining. The weight of workpiece was measured before and after machining by a precision weighing machine (0.0001g) for calculating the material removal rate (MRR). The arithmetic mean roughness (R_a) was employed to evaluate surface roughness of specimens. This measurement was performed with the help of surface tester SJ-210-MITUTOYO. The cut-off length and measuring speed were set as 0.8 mm and 0.5mm/s respectively.

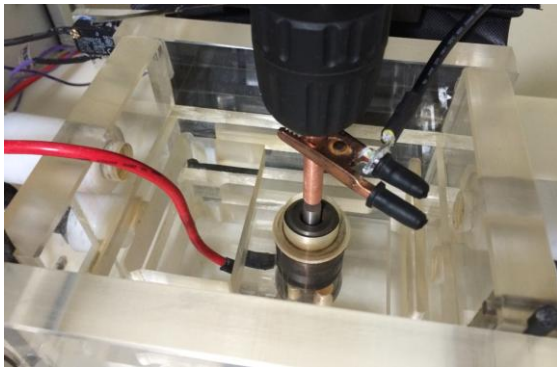


Fig. 2 Machining chamber with workpiece and tool.

3. Design of Experiments (DOE)

Experimental plan and conditions

The machining was carried out for a fixed time interval of 2 min and an initial gap distance was 0.6 mm. In the present study, the experimentation strategy was considered based on central composite second order rotatable design (CCD) for the purpose that the higher-order input parameters effects and their interactions on machining responses were determined. The values of four process inputs and their levels are shown in Table 1. Therefore, the design consists of 31 runs, in which 16 factorial points, 8 axial points, 7 center points for estimating the experimental error and the central composite parameter α was considered 2 to ensure a rotatable design. Table 3 presents the values of machining responses, i.e. MRR and R_a according to experimentation plan with various sets of machining parameters, i.e. voltage (x_1), tool feed rate (x_2), electrolyte flow rate (x_3) and electrolyte concentration (x_4). Fig. 3 shows the sample workpieces before and after machining.

Table 1: The independent ECM process factors and their levels.

Factors	Symbol	Unit	Levels				
			-2	-1	0	1	2
Voltage	x_1	V	10	15	20	25	30
Tool feed rate	x_2	mm/min	0.2	0.3	0.4	0.5	0.6
Electrolyte flow rate	x_3	l/min	5	6	7	8	9
Electrolyte concentration	x_4	g/l	50	100	150	200	250

Response Surface Methodology (RSM):

In this research, Response Surface Methodology (RSM) was applied, as one of DOE methods, for determining how the

machining parameters influence machining responses. RSM is a powerful way for building the relationship between machining parameters and responses that are useful for the modeling and analysis of the problems; accordingly, the relationship mathematically and statistically could be developed by second-order polynomial as follows:

$$y = b_0 + \sum_i^k b_i x_i + \sum_i^k b_{ii} x_i^2 + \sum_{i,j}^k b_{ij} x_i x_j + \varepsilon \quad (1)$$



Fig. 3 Workpiece after and before machining.

Where y is the desired response, e.g. MRR and R_a in this paper, x_i is the uncoded or coded levels of the independent variables, and ε is the fitting error. Also, the coefficient b_0 is the constant value or intercept and the coefficients b_i , b_{ii} and b_{ij} represent the linear, quadratic and interaction terms respectively [10].

Table 3: Central composite design plan matrix and results.

Exp. No.	Factors				Responses	
	x_1	x_2	x_3	x_4	MRR (g/min)	$R_a(\mu\text{m})$
1	-1	-1	-1	-1	0.1253	0.76
2	1	-1	-1	-1	0.2134	1.08
3	-1	1	-1	-1	0.1547	0.89
4	1	1	-1	-1	0.2361	1.13
5	-1	-1	1	-1	0.1246	0.84
6	1	-1	1	-1	0.2107	1.16
7	-1	1	1	-1	0.1569	0.96
8	1	1	1	-1	0.2525	1.31
9	-1	-1	-1	1	0.1673	1.29
10	1	-1	-1	1	0.2921	1.94
11	-1	1	-1	1	0.1975	1.63
12	1	1	-1	1	0.3218	2.21
13	-1	-1	1	1	0.1779	1.47
14	1	-1	1	1	0.2979	2.15
15	-1	1	1	1	0.2019	1.78
16	1	1	1	1	0.3235	2.49
17	-2	0	0	0	0.1154	1.22
18	2	0	0	0	0.3379	2.17
19	0	-2	0	0	0.1989	1.12
20	0	2	0	0	0.2755	1.51
21	0	0	-2	0	0.1927	1.12
22	0	0	2	0	0.2194	1.35
23	0	0	0	-2	0.1365	0.72
24	0	0	0	2	0.2696	2.45
25	0	0	0	0	0.2351	1.00
26	0	0	0	0	0.2291	0.98
27	0	0	0	0	0.2250	1.02
28	0	0	0	0	0.2238	0.96
29	0	0	0	0	0.2220	1.04
30	0	0	0	0	0.2275	0.95
31	0	0	0	0	0.2232	1.02

4. Validation and Analysis of Models

Adequate and suitable measures, tests and analyses were examined the models, so the fitness of the models to the experimental data, significant and insignificant parameters and adequacy of models were analyzed; that is, the analysis of variance (ANOVA) and the F-ratio test have been executed to check the goodness of the mathematically modeled fittings. Moreover, the R-squared ($R\text{-Sq}$) and adjusted R-squared ($R\text{-Sq}(\text{adj})$) is used for

assessing the modeling goodness of fit, as more the R^2 approaches unity, the better the model fits the experimental data. Indeed, the best condition of analysis of effective models happens as the lack-of-fit is insignificant. Then, a student's t-test has also been performed for determining the significance of each parameter in the models. Accordingly, insignificant terms have been eliminated from the models, and ANOVA has been done again through the available significant terms.

Mathematical modeling of MRR:

According to the model explained by Eq. 1, Table 3 details the ANOVA and F-ratio test information about MRR response. On the grounds that the p-value of the quadratic model is greatly less than 0.05, the model is statistically significant in the 95% of confidence interval. Besides, the p-value of the lack-of-fit is more than 0.05, so this term is insignificant which is desired. Through the ANOVA result, the MRR model is developed with coded variables as follows:

$$\begin{aligned} \text{MRR} = & -0.3374 + 0.0055x_1 - 0.0496x_2 + 0.0755x_3 \\ & + 0.00072x_4 - 1.4494E - 05x_1^2 + 0.2275x_2^2 \\ & - 0.00551x_3^2 - 2.50494E - 06x_4^2 + 0.00049x_1x_2 \\ & + 5.875E - 05x_1x_3 + 3.4875E - 05x_1x_4 \\ & + 0.0073x_2x_3 - 2.0875E - 04x_2x_4 + 9.125E - 06x_3x_4 \end{aligned} \quad (2)$$

The R^2 (R-Sq) and adjusted R^2 (R-Sq(adj)) are respectively 99.48% and 99.03% for the above MRR model ensuring an excellent fitting for the model. A student's t-test has also been performed for the determination of significant terms in the MRR model. It is concluded that all the linear terms, quadratic terms of input factors x_2 , x_3 and x_4 , and interaction effect of factors x_1 and x_4 are significant, and other terms are insignificant. The insignificant terms have been eliminated; the ANOVA have again been done to significant terms. As a result, the final reduced model of MRR based on significant parameters is developed as follows:

$$\begin{aligned} \text{MRR} = & -0.35879 + 0.00549x_1 - 0.02305x_2 + 0.08043x_3 \\ & + 0.00069x_4 + 0.23137x_2^2 - 0.00547x_3^2 - 2.48952E \\ & - 06x_4^2 + 3.48750E - 05x_1x_4 \end{aligned} \quad (3)$$

Table 3: The ANOVA results for MRR response using the Minitab software.

Source of variation	DF	Sum of Squares	Mean Squares	F value	P value
Regression	14	0.103873	0.007419	219.16	0.000
Linear	4	0.100478	0.025120	742.00	0.000
Square	4	0.002148	0.000537	15.85	0.000
Interaction	6	0.001216	0.000208	6.14	0.002
Residual Error	16	0.000542	0.000034		
Lack-of-Fit	10	0.000419	0.000042	2.06	0.195
Pure Error	6	0.000122	0.000020		
Total	30	0.104414			
R-Sq = 99.48%, R-Sq(adj) = 99.03%					

Mathematical modeling of R_a :

The same procedure is used to deal with the R_a and the ANOVA details of quadratic model are shown in Table 4. The results of the table points out that the model is significant and the lack-of-fit is insignificant according to the p-values. Based on the ANOVA result, the developed mathematical model for R_a with coded variables as follows:

$$\begin{aligned} R_a = & 8.75714 - 0.29921x_1 - 7.01905x_2 - 0.91042x_3 - 0.0234x_4 + 0.0069x_1^2 \\ & + 7.74256x_2^2 + 0.05743x_3^2 + 5.79702E - 05x_4^2 - 0.01125x_1x_2 + 0.00338x_1x_3 \\ & + 0.00035x_1x_4 + 0.08125x_2x_3 + 0.01013x_2x_4 + 0.00051x_3x_4 \end{aligned} \quad (4)$$

The R^2 and adjusted- R^2 for the R_a trimmed model are respectively 99.82% and 99.67% revealing sufficient adequacy in model predictive capabilities. The student's t-test has also been done for determining the significance of each parameter. The results of this test indicate that all linear and quadratic terms of parameters and the interaction between x_1 (voltage) and x_3 (flow rate), x_1 and x_4 (concentration), x_2 (tool feed rate) and x_4 , and x_3 and x_4 are

significant. The other model terms can be regarded as insignificant terms. By removing these insignificant terms and applying the ANOVA, the proper quadratic model for R_a can be developed as follows:

$$\begin{aligned} R_a = & 8.61964 - 0.303714x_1 - 6.6753x_2 - 0.87792x_3 - 0.0234x_4 + 0.0069x_1^2 + 7.74256x_2^2 \\ & + 0.05743x_3^2 + 5.79702E - 05x_4^2 + 0.00338x_1x_3 + 0.00035x_1x_4 + 0.01013x_2x_4 + 0.00051x_3x_4 \end{aligned} \quad (5)$$

Table 4: The ANOVA results for R_a response using the Minitab software.

Source of variation	DF	Sum of Squares	Mean Squares	F value	P value
Regression	14	7.73831	0.55274	648.07	0.000
Linear	4	6.16678	1.54170	1807.59	0.000
Square	4	1.39314	0.34828	408.35	0.000
Interaction	6	0.17839	0.02973	34.86	0.000
Residual Error	16	0.01365	0.00085		
Lack-of-Fit	10	0.00688	0.00069	0.61	0.767
Pure Error	6	0.00677	0.00113		
Total	30	7.75195			
R-Sq = 99.82%, R-Sq(adj) = 99.67%					

5. Results and Discussion

Effect of machining parameters on MRR:

Fig. 4 displays the surface and contour plot of the MRR response versus the voltage (x_1) and concentration (x_4) factors, while the tool feed rate and electrolyte flow rate factors held at middle level (0.4 mm/min and 7 l/min). The result showed that an increase in voltage and concentration leads to increase in the MRR. This is supported by the fact that by increasing both of these factors results in a higher electrolyzing current in machining gap and causing faster dissolution.

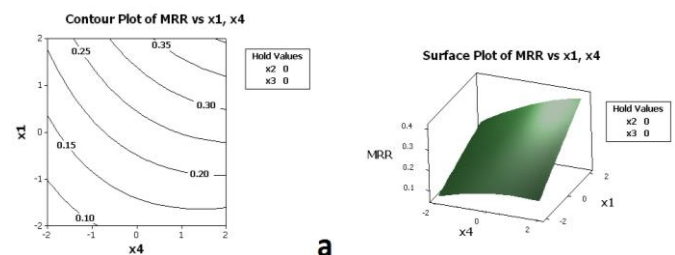


Fig. 4 Surface and Contour Plot of MRR: MRR: Voltage (x_1) and Concentration (x_4).

Moreover, Fig. 5 illustrates the surface and contour plot of the MRR response in term of voltage and flow rate of electrolyte at a constant level of sources tool feed rate and concentration kept at zero level (0.4 mm/min and 150/l). As it is shown in this Figure, high removal rate are achievable at high voltage along at low and high level of flow rate.

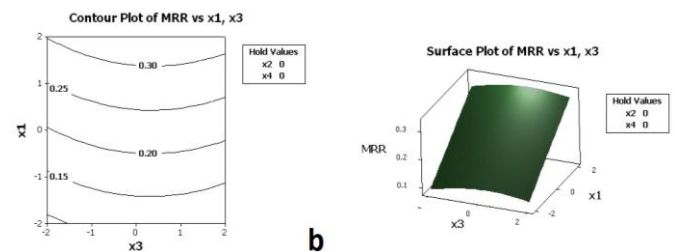


Fig. 5 Surface and Contour Plot of MRR: MRR: Voltage (x_1) and Flow rate (x_3).

Same trend can be deduced from Fig. 6. This Figure is the surface and contour plot of the MRR response versus concentration and flow rate of electrolyte at middle level of other factors. Increasing in voltage and concentration at low level of electrolyte flow rate causes steady flow of electrolyte and at high level of electrolyte flow rate causes better flushing in machining gap; thus, the conductivity and as a result the current density increase which causes high metal dissolution.

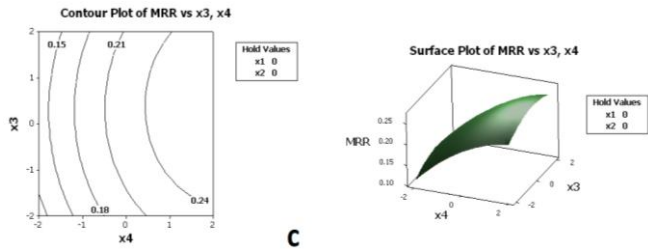


Fig. 6 Surface and Contour Plot of MRR: Flow rate (x_3) and Concentration (x_4).

Effect of machining parameters on R_a :

Fig. 7 displays the R_a response based on the voltage (x_1) and electrolyte flow rate (x_3) and the value of tool feed rate and electrolyte concentration were kept fixed at zero level. Analyzing the 3D surface plot, it concluded that high level of voltage and electrolyte flow rate deteriorate the surface finish. Also, by increasing the electrolyte flow and decreasing the voltage, the surfaces finish boots. As by increasing in voltage, the metal dissolution grows then faster flow of electrolyte helps the proper flushing of electrolyte in the IEG. From the contour plot, it is noted that for improving the better surface quality, choosing the voltage and flow rate of the electrolyte in middle to low level gives better selections.

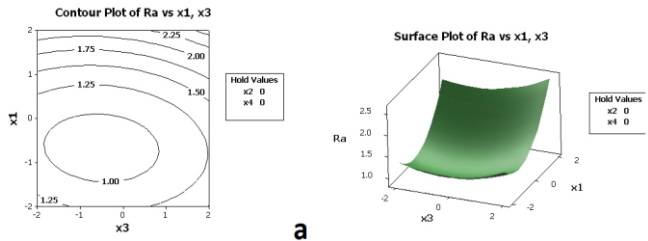


Fig. 7 Surface and Contour Plot of R_a : Voltage (x_1) and Flow rate (x_3).

Furthermore, the surface and contour plot of R_a response versus the voltage (x_1) and electrolyte concentration (x_4) at zero level of tool feed rate and electrolyte flow rate is shown in Fig. 8. It can be inferred that the surface finish gets better condition as the voltage and the electrolyte concentration decreasing. The electrolyte concentration in this study was considered in wide range from 50 g/l to 250 g/l. From the surface plot it can be concluded that at the high level of voltage and concentration lead the worst surface finish. Also, the contour plot shows that the concentration between 50 to 100 g/l and decreasing in the machining voltage from middle to low level provide the best selection for these inputs parameter on the R_a response.

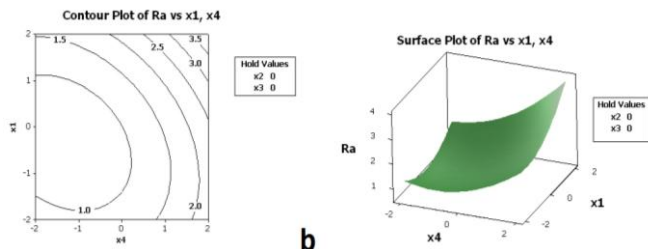


Fig. 8 Surface and Contour Plot of R_a : Voltage (x_1) and Concentration (x_4).

Fig. 9 shows the effect of the electrolyte flow rate (x_3) and the electrolyte concentration (x_4) parameters on the R_a response as 3D surface and contour plot while the other two parameters, voltage and tool feed rate, held at middle level. As can be seen from these Figures, the better surface finish is occurred at low level of concentration. Also, the low level of flow rate and high level of concentration worsen the surface finish greatly since at this condition, the poor flushing of electrolyte in the inter electrode gap (IEG) results in higher R_a .

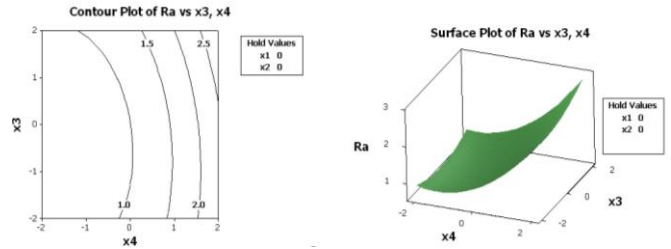


Fig. 9 Surface and Contour Plot of R_a : Flow rate (x_3) and Concentration (x_4)

6. Conclusions

This study highlights that the electrochemical machining of 321 stainless steel criteria, i.e. MRR and R_a are greatly influenced by the different machining parameters. To sum up, the followings can be acquired from this investigation as main findings:

- ❖ For gaining the model that covers all linear, quadratic and interaction terms, the RSM method has been appointed properly as the DOE method for resolving curvature in ECM process responses.
- ❖ Mathematical models have been developed through the RSM method for correlation the machining parameters, i.e. voltage, tool feed rate, electrolyte flow rate and concentration on the machining criteria, i.e. MRR and R_a , of 321 stainless steel.
- ❖ According to the ANOVA and student t-test, among the process parameters, the machining voltage and electrolyte concentration are the most effective factors on the machining criteria.
- ❖ Increasing voltage and electrolyte concentration lead to increase in the MRR. Also, the proper flushing of electrolyte improves MRR which can be regulated by the electrolyte flow rate.
- ❖ According to the wide range of voltage (10 – 30 v) and electrolyte concentration (50 – 250 g/l NaNO₃ solution), the surface quality is improved by decreasing in voltage and decreasing in concentration.

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DESALINATION BY FLUE GAS HUMIDIFICATION-DEHUMIDIFICATION USING TWO DIFFERENT FLUE GAS COMPOSITIONS

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Abstract: The objective of the work is to utilize waste heat from power stations' flue gases in desalination of seawater by humidification-dehumidification. Two power station fuels namely fuel oil and natural gas are considered. The two fuels differ in composition, calorific value, and usage of percent excess air requirements. In order to achieve the same electric power production, the composition (moisture content and specific heat) and amount of flue gases ensuing from combustion of the above two fuels will be different. One humidification-dehumidification desalination scheme is generated and results are compared with respect to the anticipated cost of produced water versus the source of flue gases. Cost is calculated on the basis of energy balance and design equations. The scheme includes: preheating of seawater using hot flue gas, humidification of an air stream by direct contact with seawater, and dehumidification of the same stream by indirect cooling in a condenser. In case of fuel oil combustion, desulphurization of the flue gas by seawater is also included. The cost of produced fresh water includes the fixed cost of heat exchangers, condensers, humidifiers, packing, pumps and fans based on the cost index of 2018, and the operating cost is based on the current electricity cost. The results show that the total cost of the produced water is much less in the case of using flue gases ensuing from natural gas fueled power stations. This happens because the flue gases in this case have a very high humidity ratio which will result in the condensation of a significant amount of water on cooling. As a result, the total amount of fresh water produced is greater than in the case of fuel oil flue gases.

Keywords: DESALINATION; SEAWATER; HUMIDIFICATION; DEHUMIDIFICATION; FLUE GAS; DESIGN

1. Introduction

Water desalination has always been an important source of fresh water in many regions and communities, especially in coastal areas that are far away from any reliable source of fresh water. Through the years, people have been developing many techniques to get fresh water from seawater. Since desalination in general is a high energy consuming process, more and more optimization and integration techniques have been applied to the process in order to produce fresh water with the least possible cost.

These techniques need accurate mathematical models to be as efficient as possible. One of the most important variables in these models is the water physical properties which vary with temperature and concentration, which change widely in any desalination process¹.

Also the available source of energy is one of the most decisive factors to choose the suitable technique in each case. Some techniques can operate perfectly on waste energy or solar energy, while other techniques operate by electricity. Some techniques also can be integrated with other industrial processes, saving both energy and logistic resources^{2,3}.

This work aims to investigate the performance of a humidification-dehumidification seawater desalination system that operates on waste energy in the form of hot flue gases from electric power stations that operate on either Heavy Fuel Oil or Natural Gas. An additional processing step may be added to this integrated system in order to remove SO₂ from the flue gas, if present.

2. Fuel and Flue Gas

The quantity and composition of the emitted flue gases depend on the rated power plant electrical power generation capacity and the type of fuel burned. Heavy fuel oil (mazot) and natural gas will be considered as fuel sources. The composition of the flue gas is calculated on the basis of typical fuel compositions and the corresponding air to fuel ratio as commonly used with natural gas and heavy fuel oil. The amount of flue gas generated per kWh is based on the calorific value of each fuel and the reported industrial values of the power plant efficiencies.

Based on the typical compositions of heavy fuel oil and Natural Gas, taking the average amount of excess air needed for combustion of fuel as 15% in case of Fuel Oil and 5% in case of Natural Gas, the composition of the flue gases was calculated using simple

material balance equations. The humidity ratio in both cases could thus be calculated on the basis of the previous calculations.

The calorific value (CV)⁴ of the fuel and the electric generation efficiency η ⁵ are used to estimate the fuel rate need in generating electricity (per kWh) and hence the amount of flue gas produced. The calculated data are presented in Table 1.

Table 1: Flue Gases Compositions and Fuel Ratings

Fuel		Fuel Oil	Natural Gas
% excess air		15	5
C.V.	MJ/kg	41	47.3
	kWh/kg	11.39	13.139
FG composition by mass	CO ₂	0.179	0.141
	H ₂ O	0.057	0.11
	SO ₂	0.003	0
	O ₂	0.028	0.01
	N ₂	0.733	0.738
η %		30	30
Humidity Ratio, (kg water/kg drygas)		0.060185	0.12413
fuel rate	kg/kWh	0.2927	0.2537

3. The proposed Desalination Scheme

Flue gas is used to indirectly heat a stream of seawater which will be contacted with a circulating stream of air in a counter current humidification tower. Seawater is preheated to 40°C in the humid air condenser, then part of this stream is heated to 100°C in a heat exchanger against flue gas which is cooled down to 50°C. The dehumidification condenser allows a minimum temperature approach of 10°C, which means that the saturated air will leave the condenser at 40°C. This stream will meet the hot seawater in the humidifier which will act as a cooling tower with a temperature approach of 5°C at the bottom. The leaving air stream is assumed to reach 95% of the saturation humidity. Finally the cold flue gas will be desulphurized in a counter current absorber using seawater as a solvent. Fig. 1 shows this flow scheme.

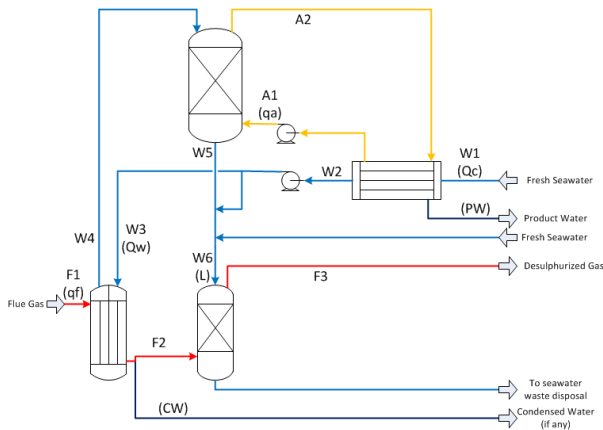


Fig. 1 Humidification-Dehumidification Desalination Scheme

4. Model

In the Flue Gas Heat Exchanger, the inlet and outlet flue gas enthalpies are given by:

$$H_{F1} = q(C_g T_{F1} + (C_w T_{F1} + \lambda) W_{F1}) \quad (1)$$

$$H_{F2} = q(C_g T_{F2} + (C_w T_{F2} + \lambda) W_{F2}) \quad (2)$$

While the inlet and outlet seawater enthalpies are given by:

$$H_w = Q_w C_p T_w \quad (3)$$

Therefore the quantity of seawater can be calculated from:

$$Q_w = (H_{F1} - H_{F2}) / (C_p T_{w2} - C_p T_{w1}) \quad (4)$$

Where Q_w : Mass flow rate of seawater (kg/h),

C_g : Specific heat capacity of air (kcal/kg.°C),

C_w : Specific heat capacity of water vapor (kcal/kg.°C),

λ : Latent heat of vaporization of water (kcal/kg),

T_{F1} : Inlet temperature of flue gas = 150°C,

T_{F2} : Outlet temperature of flue gas = 50°C,

W_{F1} : Inlet humidity of flue gas (kgwater/kgdrygas),

W_{F2} : Outlet humidity of flue gas (kgwater/kgdrygas),

C_p : Specific heat capacity of seawater (kcal/kg.°C),

T_w : Temperature of Seawater (°C),

q_f : Dry flue gas rate (kg/h)

The area of the heat exchanger can thus be obtained from

$$Area = (H_{F1} - H_{F2}) / (U_e \Delta T_m) \quad (5)$$

Where

$$\Delta T_m = ((T_{F2} - T_{w3}) - (T_{F1} - T_{w4})) / \ln((T_{F2} - T_{w3}) / (T_{F1} - T_{w4})) \quad (6)$$

U_e : Overall heat transfer coefficient (kcal/m².°C.h)

In the air humidifier, the exit temperature of the humid air is obtained by heat balance assuming that it will be 95% saturated with water vapor at this temperature. The enthalpies of the streams entering and leaving the humidifier are given by:

$$H_{A1} = q(C_g T_{A1} + (C_w T_{A1} + \lambda) W_{A1}) \quad (7)$$

$$H_{W4} = Q_w C_p T_{W4} \quad (8)$$

$$H_{W5} = (Q_w - qa(W_{A2} - W_{A1})) C_p T_{W5} \quad (9)$$

$$H_{A2} = q(C_g T_{A2} + (C_w T_{A2} + \lambda) W_{A2}) \quad (10)$$

Where qa : Dry air recirculation rate (kg/h)

T_{A1} : Inlet temperature of air (°C)

T_{A2} : Outlet temperature of air (°C)

W_{A1} : Inlet humidity of air(kgwater/kgdrygas)

W_{A2} : Outlet humidity of air(kgwater/kgdrygas)

Given the percent saturation of air and by mass balance, the relation between T_2 and W_2 may be expressed as

$$W_{A2} = 0.95(T, C) P_t - P(T, C) M_w M_a \quad (11)$$

Where $P(T, C)$: Vapor pressure of seawater at temperature (T) and concentration (C) (mmHg),

P_t : Total Pressure (mmHg), M_w : Molecular weight of water (g/mol), M_a : Molecular weight of air (g/mol)

The concentration of seawater leaving the humidifier is calculated from:

$$C_{W5} = C_{W4} Q (Q_w - qa(W_{A2} - W_{A1})) \quad (12)$$

The volume of the humidifier can thus be calculated as

$$V_p = H_{W4} - H_{W5} / (k_p \Delta T_m) \quad (13)$$

Where V_p : Volume of the packed section (m³)

$$\Delta T_m = ((T_{W4} - T_{A2}) - (T_{W5} - T_{A1})) / \ln((T_{W4} - T_{A2}) / (T_{W5} - T_{A1})) \quad (14)$$

k_p : Volumetric heat transfer coefficient in the packed section

(kcal/h.m³.°C)

Assuming an exit gas velocity of 1.5 m/sec and given the density of the exit gas and the number of in parallel needed columns, the cross section area of each column can be calculated from

$$Area = qa / (\rho v N) \quad (15)$$

Where ρ : Exit gas density (kg/m³),

v : Exit gas velocity (m/s), N : Number of columns

In the fresh water condenser, the amount of condensed water is calculated from the inlet humidity of humid air and its saturated humidity after being cooled.

$$Cond. Water (PW) = qa(W_{A2} - W_{As}) \quad (16)$$

The amount of seawater used for cooling is calculated from the enthalpy difference between the inlet and the outlet air, given the inlet seawater temperature and assuming its outlet in order to maintain a specific temperature approach.

$$Q_{sw} = H_{A2} - H_{A1} C (T_{w1} - T_{w2}) \quad (17)$$

The heat transfer area is calculated from

$$Area = H_{A2} - H_{A1} U_c \Delta T_m \quad (18)$$

Where

$$\Delta T_m = ((T_{A1} - T_{w1}) - (T_{A2} - T_{w2})) / \ln((T_{A1} - T_{w1}) / (T_{A2} - T_{w2})) \quad (19)$$

U_c : Overall heat transfer coefficient (kcal/m².°C.h)

5. Input Conditions

4.1. Flue Gas

For flue gas generated from the combustion of Fuel Oil, a basis of 400,000 kg/h will be used at a temperature of 180°C⁶. Based on typical fuel oil composition, combusted with 15% excess air, the flue gas will have a humidity of 0.060185 kg water/kg dry gas, SO₂ concentration of 0.0994% by weight, and an average molecular weight of 29.13135.

While in the case of power plants operating on Natural Gas, the basis for the generated flue gas will be 200,000 kg/h at 150°C. Based on its typical composition, combusted with 5% excess air, it will have a humidity of 0.12413 kg water/kg dry gas, it will be SO₂free, and will have an average molecular weight of 27.75788.

The temperature of seawater is assumed to be 30°C, which should be the maximum temperature in summer. The concentration of salts is taken as 35 ppt (parts per thousand).

4.2. Physiochemical parameters

Since the process involves a change in the salt concentration in the seawater, seawater properties such as vapor pressure and specific heat capacity will be related to both temperature and concentration using suitable correlations¹.

The specific heat capacity of dry air (C_g) is taken as 0.24 kcal/kg.°C, while that of water vapor (C_w) is equal to 0.45 kcal/kg.°C. The latent heat of vaporization of water (λ) is equal to 597.33 kcal/kg at the reference temperature.

4.3. Transport parameters

The heat transfer coefficients in the gas-seawater heat exchangers (U_e) and in the scrubber filled with wooden lath packing (K_p) are taken as follows⁷

$$U_e = 137.5 \text{ kcal/h.m}^2.\text{°C}, \quad K_p = 875 \text{ kcal/h.m}^3.\text{°C}$$

6. Results

The calculations were made in the two cases discussed earlier; using Fuel Oil or Natural Gas Flue Gas. The previous equations were used to get the process data and the design data in each case. Then the cost of producing fresh water was calculated. The cost is mainly divided into two parts: Fixed Cost and Operating Cost. Fixed Cost includes the costs of the heat exchangers, condensers, humidifiers, packing, pumps, and fans based on the cost index of 2018⁸. While the operating cost includes the costs of pumping the water and circulating the gases. The annual total cost is calculated by adding the annualized fixed cost of the various equipment, assuming a twenty year service life, to the annual operating cost⁹. The currency conversion rate was taken at \$1=EGP17.8.

5.1. Using Fuel Oil Flue Gas

Figures 2-5 show the variation of the design data of the different equipment, and the variation of seawater requirements with the variation of the air circulation rate for the same hot seawater consumption.

5.2. Using Natural Gas Flue Gas

Figures 6-9 show the variation of the design data of the different equipment, and the variation of seawater requirements with the variation of the air circulation rate for the same hot seawater consumption.

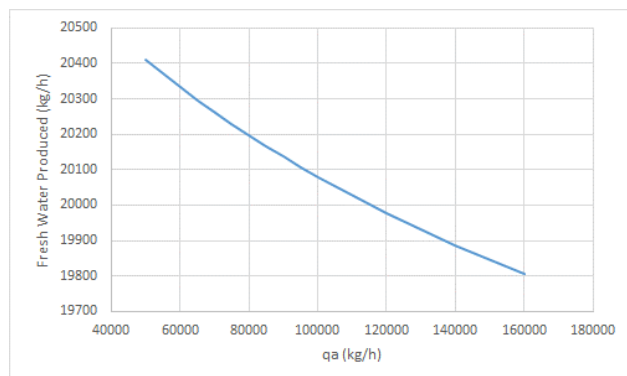


Fig. 2 Fresh Water Produced vs. Air Circulation Rate – F.O. Flue Gas

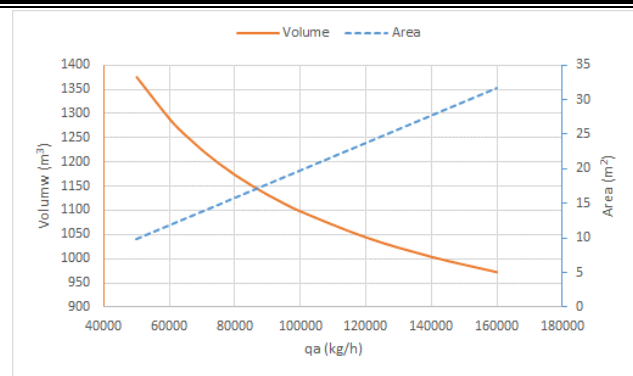


Fig. 3 Humidifier Area and Volume vs. Air Circulation Rate – F.O. Flue Gas

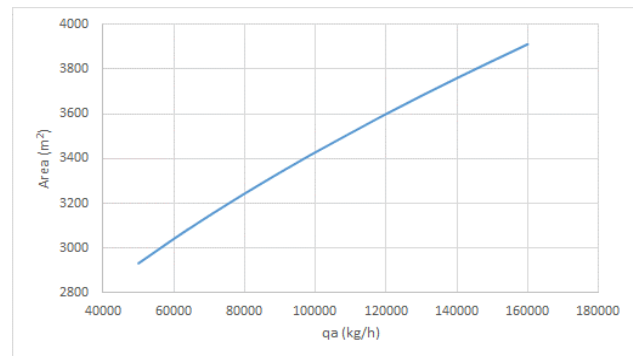


Fig. 4 Condenser Area vs. Air Circulation Rate – F.O. Flue Gas

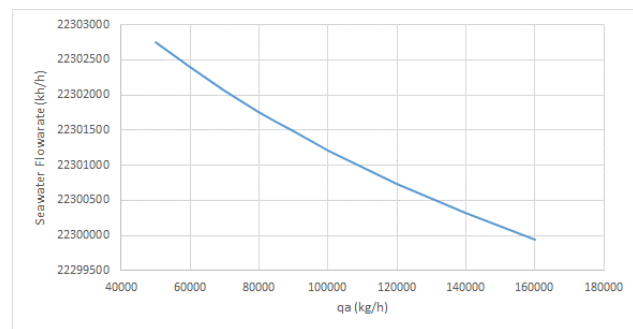


Fig. 5 Seawater Requirements. Air Circulation Rate – F.O. Flue Gas

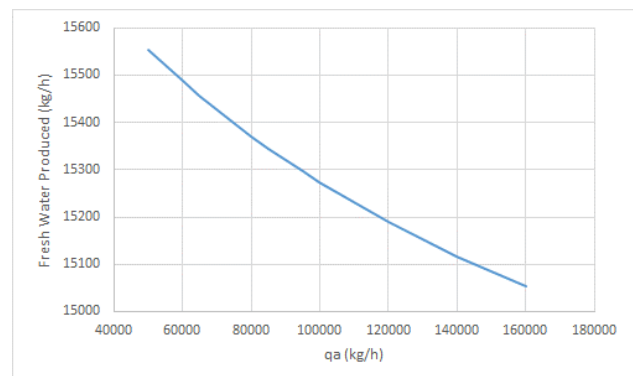


Fig. 6 Fresh Water Produced vs. Air Circulation Rate – N.G. Flue Gas

5.3. Total Production Cost

The only variable in this scheme was the flow rate of the circulating air. It was found that the fixed cost of the heat exchanger will remain constant, while all the other fixed and operating costs will increase with the increase in the circulation rate except for the fixed cost of the empty columns, the packing, the pumps, and the pumping operating cost. The cost of packing decreases as the

volume of the packing decreases on increasing the circulation. The other costs will vary with the total number of columns that depend on the height and diameter limitations.

It was found that the recommended scenario, with the least value of the total cost, is at the smallest air circulation rate.

Figure 10 compares between the variations of the total annual cost per m3 of produced water with the air circulation rate in both cases.

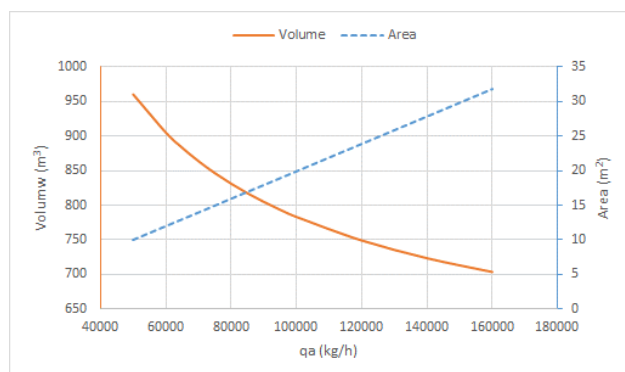


Fig. 7 Humidifier Area and Volume vs. Air Circulation Rate – N.G. Flue Gas

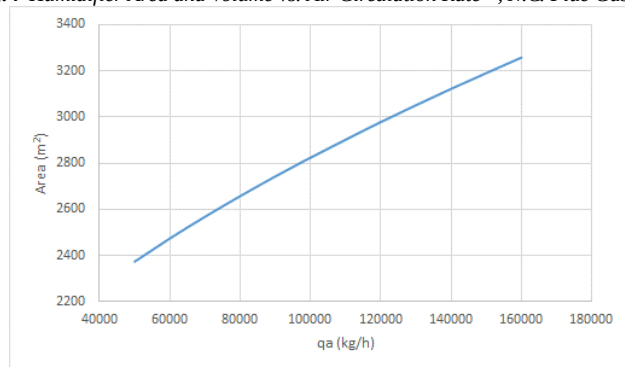


Fig. 8 Condenser Area vs. Air Circulation Rate – N.G. Flue Gas

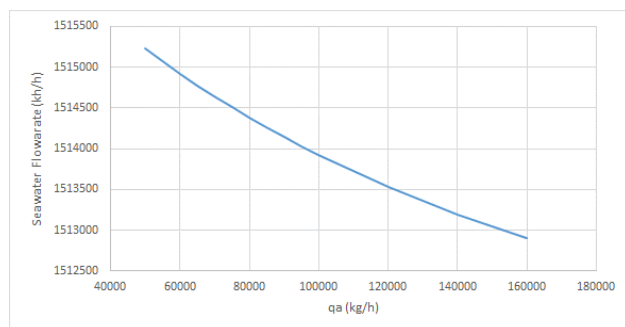


Fig. 9 Seawater Requirements. Air Circulation Rate – N.G. Flue Gas

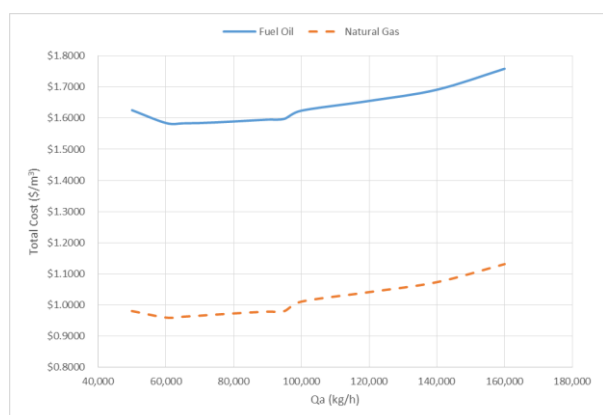


Fig. 10 Total Production Cost of Fresh Water vs. Air Circulation Rate

7. Conclusion

This work is concerned with the utilization of waste heat from power stations' flue gases in seawater desalination. The flue gases used in the process are produced from electric power stations that operate on either heavy fuel oil or natural gas. The type of fuel affects the composition and the quantity of the produced flue gases. A process scheme was proposed to desalinate seawater by the humidification-dehumidification technique utilizing the flue gases. The scheme include the following processes: indirect preheating of seawater using hot flue gases, humidification of an air stream by direct contact with seawater, dehumidification of the same stream by indirect cooling in a surface condenser using cold seawater, and an absorption step to desulphurize the flue gases in case of using fuel oil flue gases.

The results were compared with respect to the cost of the produced fresh water. The cost was calculated based on material balance, energy balance, and equipment design equations. The cost includes the fixed cost of the exchangers, condensers, humidifiers, packing, pumps, and fans based on the cost index of 2018. It also includes the operating cost of pumps and fans based on the current cost of electricity.

Results have shown that using the flue gases produced from natural gas power stations will produce fresh water with less total cost than the case of fuel oil flue gases. A significant amount of water will be condensed on cooling the flue gases ensuing from burning natural gas owing to their high humidity ratio, which will result in increasing the total amount of fresh water produced.

For future work, it is recommended that more parameters should be varied to study their effect on the cost and rate of water production such as the minimum temperature approaches in the exchangers or the humidifiers.

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AUTOMATED 2D LASER SCANNING SYSTEMS FOR INVESTIGATIONS OF SOLID SURFACES

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Abstract: Automated optical scanning systems for analysis of solid surfaces are presented in this work. The prototypes are capable of detecting various parameters and irregularities related to the surfaces of solid bodies by measuring the amplitude of modulated signals of the Electromagnetic Echo Effect. The systems allow various sizes of all kinds of surfaces to be scanned and the results to be visualized on a computer screen. The aim of this work is to present two prototype versions (which use analogue and digital measuring devices) and to show their capabilities. Their general purpose is to scan different areas of specimens and visualize their sensitivity to the Electromagnetic Echo Effect onto a plot of coordinates but they are also capable of providing valuable information about structural, mechanical and electrical surface parameters.

Keywords: SCANNING SYSTEM, LASER RADIATION, SOLID SURFACES, IRREGULARITIES, ELECTROMAGNETIC ECHO EFFECT

1. Introduction

The investigation of the surface properties of materials is an important task with applications in chemistry, physics, technology, industry, etc. [1-3]. In recent years, together with tactile profilometers, which are among the most commonly used roughness measuring devices, some optical and other methods for surface characterization have been developed. Some of them require contact to be made with the sample, for example, when scanning with a stylus, which could lead to some destruction of the surface under investigation. There also exist techniques, which employ only very weak interactions with the surface, such as the atomic-force microscopy (AFM) [1]. Others, like the scanning electron microscopy (SEM) and the transmission electron microscopy (TEM), irradiate the sample with a beam of electrons and, thus, no contact with the surface is made [4].

Such instruments offer high precision and resolution (from several nanometres to several hundred micrometres), but are very complex, expensive and require skills to be operated. They also demand special preparations of the sample and the use of a vacuum chamber, where the irradiation with electrons is performed.

The abovementioned devices provide information mainly about the topology of the investigated surfaces and eventually their roughness. No single apparatus exists, which is capable of obtaining information about a large spectrum of surface characteristics.

2. Prerequisites and means for solving the problem

We have developed a simple and fast method for surface characterization via optical systems for 2-dimensional scanning of solid surfaces of all kinds of materials through irradiation with a modulated laser beam and induction of the Electromagnetic Echo Effect (EMEE), formerly known as the Surface Photo-charge Effect (SPCE). SPCE is the working name of grouped results obtained. In 2019, it was proposed to change this working name to “Electromagnetic Echo Effect” (EMEE), since it more accurately describes the experimental results obtained later and better reflects the nature of the effect. In addition, in this way it will not be confused with the Photoelectric Effect. The EMEE is represented by small voltage, detected in all kinds of materials, when illuminated by an electromagnetic field [5]. It is very fast and with the appropriate equipment, it is possible to build a scanner operating on that principle [6]. This method is sensitive, non-destructive, cheap, fast and easy for implementation.

The purpose of the systems is to measure the response (sensitivity) of various samples to the EMEE, in order to evaluate their surface condition and suitability for integration as working surfaces into a new type of sensors based on laser radiation-solid interactions. One of the most promising materials for working surfaces are silicon wafers. These automated scanning devices are improved versions of a similar system developed for investigation of conductive materials [7]. They have actually been modified and optimized for the purpose of detecting “special” points on the working surfaces, which have much stronger response to EMEE than the rest of the surface. The system have been built for development of a new type of fog sensors under a European project related to security. Since the signals from EMEE are very weak, it is essential to find these small areas and construct a “sensitivity map”. This would allow better and stronger signals to be measured and, thus, the efficiency of the sensors to be improved significantly.

The scanning systems complement the range of scanning devices, such as SEM and TEM, since they cover larger areas of several centimetres squared. The scanning systems are automated, easy to operate with, they do not require special conditions, such as vacuum, and no special preparation of the sample is needed. Technical modifications can be made, so that they can scan larger or smaller areas. Similar systems, which use ultrafast shear acoustic waves [8], photo-structural changes [9], etc., are also available.

Currently, no other single instrument exists, which is capable of detecting a large variety of surface structural characteristics, such as: mechanical defects, changes in surface electrical characteristics, surface states, chemical composition, the presence of impurities, etc.

In order to better understand, the nature of the scanning systems and their principles of operation, we will shortly discuss the phenomenon that causes generation of the signal of interest, namely the Electromagnetic Charge Effect (EMEE). In different sources, phenomena very similar to EMEE have been referred to as Surface Photo-Charge Voltage (SPCV or SPV), Photocharge Voltage (PV) and others. The measurement of the EMEE is contactless and fast. An important characteristic of this effect is its significant dependence on the specific properties of the irradiated sample. The amplitude of the EMEE response depends on the type of the irradiated material. This allows for discrimination between different materials, which opens a wide area of analytical applications and reveals vast opportunities for rapid and contactless analysis of solids, liquids and gases.

The EMEE is a phenomenon consequent to electromagnetic field-matter interactions. Its essence is that upon irradiation with an

electromagnetic field, all solid bodies generate an alternating potential difference at their surface, the frequency of which is equal to the frequency of the incident electromagnetic wave. This potential difference between the irradiated sample and the common electric ground of the system can be measured with an electrode, which can be either in contact with the solid body, or in near proximity; but there is no mandatory need for contact – the measurement can be entirely contactless. A principle scheme is illustrated in Figure 1, where a solid body's surface potential is measured via an electrode.

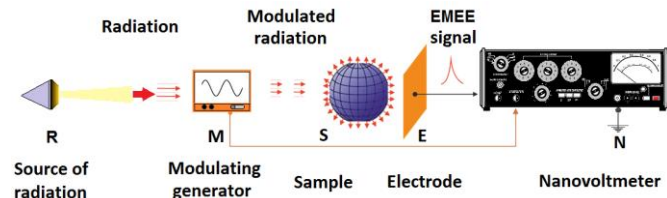


Figure 1. A general scheme for EMEE observation: (L) electromagnetic radiation source, (M) radiation modulating generator, (S) irradiated solid sample, (E) signal measuring electrode, (N) signal measuring device – nanovoltmeter

It has to be noted though, that since the EMEE is a relative measurement, it has to be taken with respect to the steady state. This leads to a limitation in the measurement of the effect. It can only be measured by inducing it with modulated light. The process itself is quite fast. It has been observed that a 20 ns laser pulse is more than enough to change the surface potential and generate a full waveform of the output signal [10]. In fact, EMEE has been registered with modulation frequencies all the way between 1 Hz and 1 GHz. EMEE has also been observed in a wide range of the electromagnetic spectrum – from the infrared, throughout the visible and up to the beginning of the ultraviolet spectrum [10]. The measured value of EMEE can depend on many factors. Some of them are: intensity of irradiation, wavelength, area of irradiated region, surface condition, surface structure, chemical composition, material type etc. [11]. Carefully choosing an appropriate wavelength, for example, can maximize the levels of the generated voltage, since different wavelengths generate electron-hole pairs at different depths inside the surface, which directly affects the generated EMEE.

EMEE has been observed in many types of solids, including not only conductors and semiconductors, but also dielectrics [10]. It is however most useful for investigation of semiconductor materials, as it can be used for characterizing and studying poorly understood compound semiconductors, where other common methods using the fabrication of ohmic contacts or special device structures may be difficult. [12] This also means that methods of investigation of semiconductors via EMEE can be quite valuable for developments in electronics. This effect can be used to measure the minority carrier diffusion length. This measure is critical for determination of the performance of devices, such as photo conducting detectors and bipolar transistors. In both cases, the ratio of the diffusion length to the device dimensions determines the gain. Other common uses include the detection and localization of different impurities and defects that limit (or boost, depending on the use) device performance. For example, EMEE can be used to measure the density of impurity-derived recombination centres. [12] Some other noted possible applications that take advantage of the fast and contactless measurement include quality control of the composition of various goods during manufacturing (e.g. bricks [11], milk [13]), chemical composition tests (e.g. detection of counterfeit coins [10]) and different remote sensors (e.g. fluid level sensor [14]). In contrast to other similar effects, the EMEE is a characteristic of all kinds of solids and this makes it very interesting from scientific as well as from practical point of view. By this method one can obtain valuable information about the irradiated solid surfaces, namely about the presence of mechanical defects and imperfections, impurities and surface states, surface electrical characteristics such

as a type of conductivity, etc. One can trace the shape of the produced surface structures, for example, by ion implantation.

3. Solution of the examined problem

Prototypes of a measurement system based on the EMEE have been developed by using different technical implementations. Here we present two of them. The systems have been built, tested and are currently operating. They are capable of detecting various parameters related to the surface of solid surfaces by measuring the amplitude of modulated signals obtained by EMEE.

Their general purpose is to scan different areas of specimens and visualize their sensitivity to EMEE onto a plot of coordinates. To do that, automated movement and automated measurement are needed. For the movement, a dual-axis linear stage is used. It is driven by a pair of step motors and controlled by its own controller. This controller can then be used to drive the stage programmatically from a PC. The measurement principle – the signal is modulated, so that a nanovoltmeter can lock to the same frequency and measure the low amplitude with an enormous noise cancellation. The measurement device is fully or partially controllable via a computer interface. The principle block diagram is shown in Figure 2.

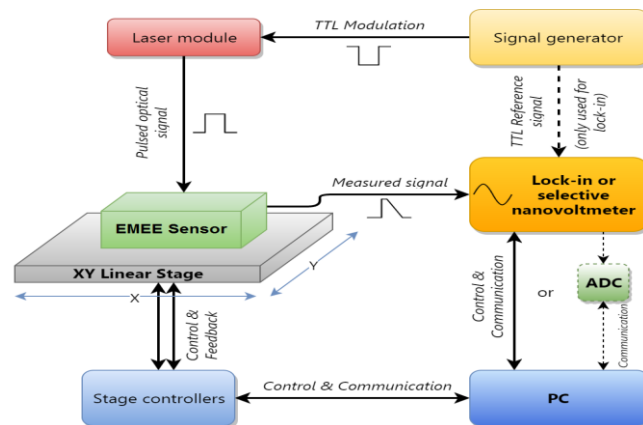


Figure 2. Block diagram of the automated EMEE scanning systems for solid surfaces

The generator of the signal of interest is an EMEE sensor, which often has an integrated semiconductor wafer inside playing the role of a working surface. Internal specifics about this sensor will not be discussed here, due to confidentiality considerations. It will be considered as a whole unit integrated into the system. Silicon wafers are interchangeable for the purposes of their investigation along with other purposes of the system. The sample is irradiated with a modulated laser beam, which stays fixed and is aligned perpendicularly with respect to the sensor's open surface. To move the specimen relative to the laser beam, it is easier to move the whole sensor. Thus, the sensor is fixed to the surface of an XY positioning stage driven by two step motors. The system is able to move automatically the specimen to desired coordinates and measure in each point inside a predefined by the user rectangular region. It is also able to scan over a single line (horizontal, vertical or inclined), or in a single point with specific coordinates. It has been empirically discovered that the slightest movement or vibration during a measurement disrupts it. This is why the laser module should be kept fixed, only the specimen (along with its sensor) should be able to move and final measurements of each point should be taken only when both are stationary (i.e. not continuous measurement but point-per-point measurement).

If a whole "sensitivity map" of a specimen is built, one can take advantage of the distribution of sensitivity in future integration of the semiconductor wafer into produced units. The general aim is to be able to scan and visualize the sensitivity to EMEE of whole areas of the surface of different wafers and to visualize it onto a plot of

coordinates. Such areas should be represented by discrete sets of hundreds, thousands or even millions of sample points.

Due to the nature of EMEE, the best approach to extract any useful signals and results is to modulate the input signals and expect modulated output signals with the same frequency. For the purpose, a standard digital signal generator is used. Its signal controls the laser, and in turn, the pulsed beam creates very weak fluctuating electromagnetic fields inside the sensor. These fields are then sampled. A signal with the same modulation frequency in the range of nano- and micro- volts is generated (usually in the range between 200 nV and 1 mV, depending on the specimen). The system has to be well shielded from external noises (both electromagnetic fields and radiation in the visible spectrum can be considered noises to the system). Even so, noise levels in the output signal can be more than a hundred times stronger than the signal of interest. This is why specialized measurement equipment is used to filter and amplify EMEE generated signals.

The systems can currently work with two types of analogue nanovoltmeters – lock-in nanovoltmeters and selective nanovoltmeters. The output signal from the nanovoltmeters has to be digital, so either an ADC (analogue-to-digital converter) from their output can be used, or for better control over the process, fully controllable nanovoltmeters can be used.

- **The first prototype** uses an ADC coupled to an analogue selective nanovoltmeter. This configuration allows for quicker development, simpler solution and increased scanning speeds. Short name: analogue scanning system.

- **The second prototype** uses a programmable and fully controllable lock-in nanovoltmeter with an integrated processor and digital controls. This configuration offers better controllability and higher accuracy, but slower scanning speeds. Short name: digital scanning system.

These two configurations taken together allow for versatility and each of them is suitable for a different situation with specific requirements. The components of the systems are shown in Figure 3:

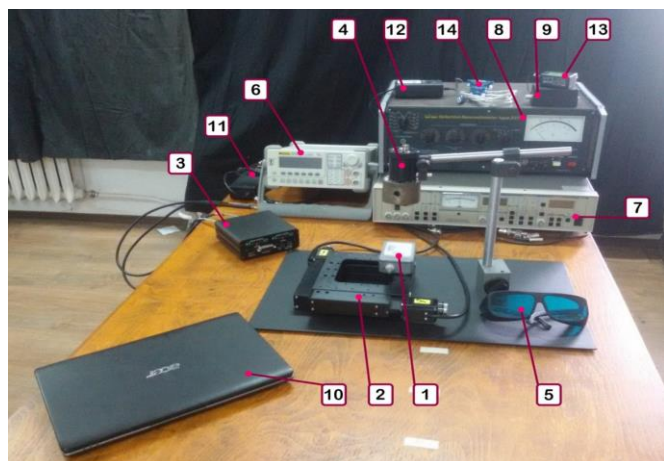


Figure 3. Photograph of the components of the automated scanning systems: 1) EMEE Sensor; 2) Dual axis linear stage Standa 8MTF-75LS0; 3) Dual-axis motor controller Standa 8SMC4-USB-B9-2; 4) Laser module Roithner Laser Technik RLDH650M-40-5; 5) Protective glasses Kentek KOS-6109; 6) Digital signal generator Rigol DG1022; 7) Lock-in nanovoltmeter SRS SR510; 8) Selective nanovoltmeter Unipan Type 237; 9) ADC converter; 10) PC or laptop; 11) Power supply Standa PUP120-17; 12) Power supply Roithner Laser Technik LPS51; 13) A standard power supply (5 VDC, 1A); 14) LogiLink UA0042A RS232-to-Serial converter.

Due to conversions and amplifications of the measured signals, the output information, which is presented to the user, does not represent the real values of the measured signals. That is why the Z-

axis of the graphs obtained with the scanning systems is in arbitrary units. This is not a problem, since the ratios of the amplitudes of the signals are kept the same as the original ones and can still be adequately compared.

4. Results and discussion

All visualizations of experimental scans show the scanned areas in the XY plane and the amplitude of the measured EMEE signals in the Z direction (in arbitrary units). All results are visualized by DPlot software.

Figure 4 shows visualizations of “special” points (irregularities) on the surface of a silicon crystal. The fog sensors that we develop use such crystals and such special points, where the efficiency is high. Efficiency, in this case, is the difference between the signals, which the sensor measures, when sensing fog of pure water and fog with impurities. The scans were performed using the analogue scanning system.

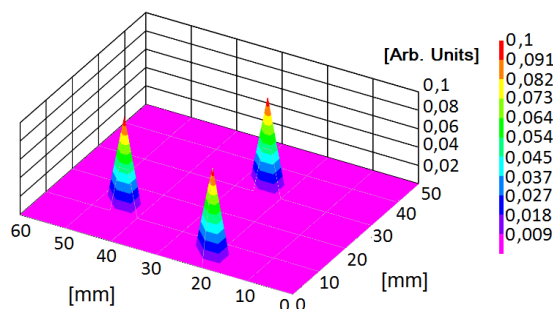


Figure 4. Experimental results – visualization of special surface points on a silicon crystal

This result shows that our systems are able to detect irregularities on the surfaces of silicon crystals.

Figure 5 shows visualizations of a droplet of distilled water at two different stages in the process of evaporation. The results in were obtained by the digital scanning system and indicate that it allows processes on surfaces to be investigated and controlled in real time.

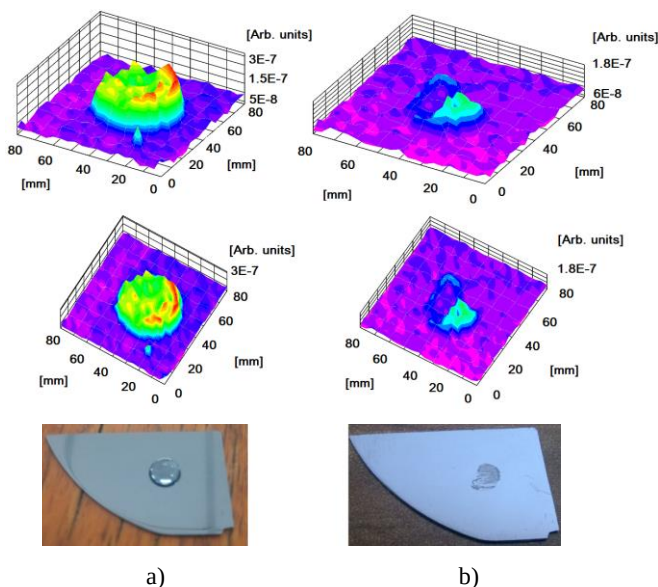


Figure 5. Experimental results – visualization of distilled water droplet: a) full droplet; b) partially evaporated droplet

Figure 6 demonstrate that our systems allow mechanical defects on surfaces to be controlled. It shows a visualization of the scratched surface of a silicon crystal obtained by the digital scanning system. It can be clearly seen that there is a good

accordance between the visualized results and the actual mechanical deformations on the surface of the silicon crystal.

A 3D visualization of the surface of an ion implanted specimen obtained by the analogue scanning system is shown in Figure 7.

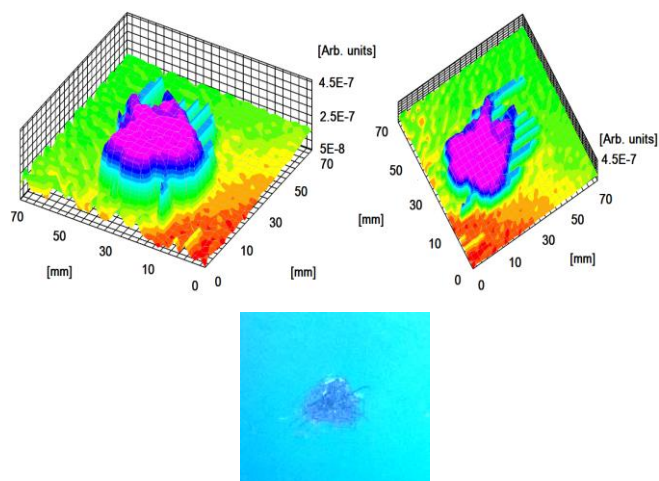


Figure 6. Experimental results – visualization of the scratched surface of a silicone crystal

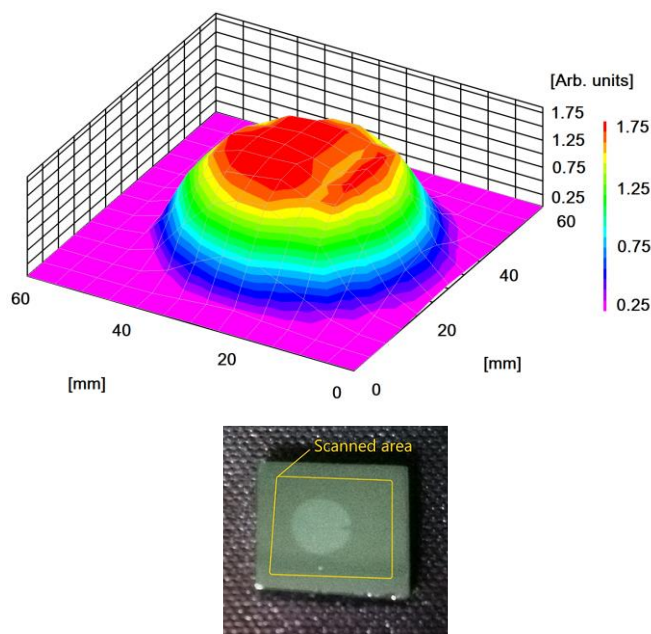


Figure 7. Results of surface scanning of an ion implanted specimen studied with the developed system

5. Conclusion

We present two versions of automated systems for optical scanning of solid surfaces and have demonstrated some of their capabilities of detecting various surface irregularities, such as: changes in chemical composition, topology, and mechanical defects. Visualizations of such scanned characteristics as 3D maps were shown. We have demonstrated that it is possible to also control ongoing processes on solid surfaces in real time. The systems were designed to perform scans of areas of several centimetres squared, but can be modified to scan larger or smaller areas. The advantages of the developed systems include simplicity, fast operation, reliability, relatively low cost, and the ability to detect various kinds of irregularities. They offer the possibility to be further developed and improved, in order to perform scans at varying depths inside solid surfaces. They can be used for quick and easy surface characterization and surface quality control.

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CALCULATION OF THE PARAMETERS ON OUTPUT CURRENT IN FULL-BRIDGE SERIAL RESONANT POWER CONVERTER

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Abstract: In this paper for full-bridge serial resonant converter, exact general equations for dependencies of phase angle, the maximum voltage of the capacitor and the maximum value of the output current are derived. Mathematical analysis of the this dependence on the resonant circuit dumping frequency when it is excited with pulse voltage with a different frequency than the resonant one is made. This dependences derived in wide a band around the resonant frequency.

Keywords: POWER CONVERTER, PHASE ANGLE, OUTPUT CURRENT, EQUATIONS

1. Introduction

In the analysis of serial resonant converters it is usual to use the resonant circuit frequency ω_0 for two reasons: 1) assuming that the value of the resistance of the resonant tank is very small the dumping is negligible and thus resonant ω_0 and damping ω_d angular frequencies have very close values; 2) active power is calculated using the phase angle between voltage and current first harmonics [1], [2], [3], [4]. However, at these converters in applications of induction heating there is an equivalent resistance of the resonant circuit and the resonant and dumping are different [5], [6], [7]. Also in these converters, the voltage waveforms are pulse and the current has a dumped sinusoidal form [8], [9]. In such cases is required the phase angle and maximum value on the output current of the converter be calculated in respect to the dumping frequency.

In this paper for H-bridge serial the resonant converter the explicit dependence of the output current of the converter from the deviation on the switching from dumping frequency is determined. This calculation is made in a wide band around the resonant frequency.

2. Calculated of the output current of the serial resonant bridge converter

Calculation of the current in wide band around the resonant frequency based on calculate the value of the phase angle and maximal value on current in this wide band.

2.1 Phase angle dependence analysis

The knowledge of the dependence of the phase angle between the output voltage and current of the bridge converter is convenient for maintenance operating the converter with constant power [10], [11], [12]. Fig. 1 shows a block diagram of the feedback control circuitry used in the direct phase control of full-bridge serial resonant converter [13], [14].

The microcontroller program has predefined values for the initial value of the switching frequency $f_{s,ref0}$ (or period $T_{s,ref0} = 1/f_{s,ref0}$) and the desired or the reference phase difference between the output voltage and current ϕ_{ref} [15]. This phase difference would be zero or close to zero if maximum power transfer is needed, or have a specific value that corresponds to the desired output power when we like to control the power transfer.

Analysis of the series-resonant converters usually use the voltage and current first harmonics to determine the circuit parameters and behavior. Assuming that the resistance in the circuit is small, the resonant frequency ω_0 is used in the calculations.

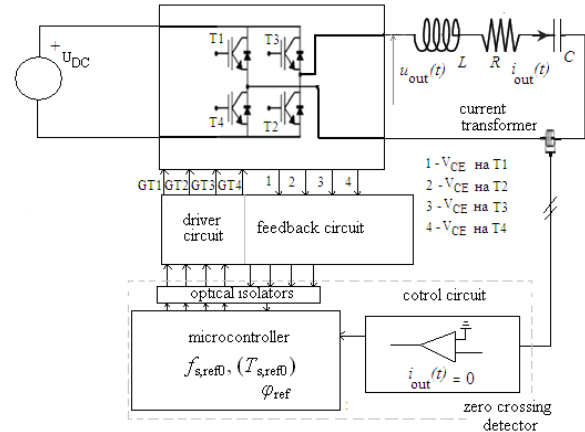


Fig. 1 Block diagram of the full-bridge series-resonant converter.

When a series resonant circuit, Fig. 2 is excited by a sine wave voltage, all waveforms have the same shape.

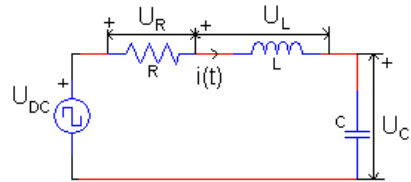


Fig. 2 Serial resonant circuit supply with voltage $\pm U_{DC}$.

When the supply voltage of serial resonant circuit is in form of the Heaviside step function, then the current oscillates around zero with angular dumping frequency ω_d , as shown in Fig. 3. When the voltage has square pulses waveform (duty ratio $D = 0.5$) and amplitude $\pm U_{DC}$, then in every half-period the current is a piece of the dumped oscillation of Fig. 3.

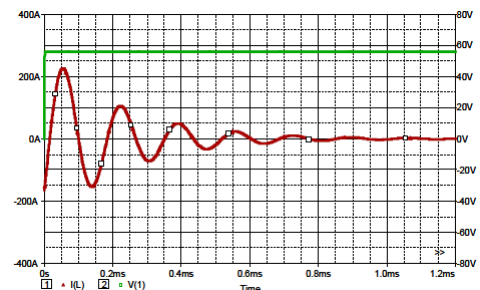


Fig. 3. Current waveform in the series-resonant circuit when excited by a Heaviside step voltage with amplitude $U_{DC} = 60$ V. Parameters' values are $R = 0.24 \Omega$, $L = 26.5 \mu H$ and $C = 26.6 \mu F$ with initial values $i_L(0+) = -165$ A and $u_C(0+) = -163$ V.

When the circuit excitation with voltage pulses, the current is in the form:

$$i(t) = e^{-\alpha t} K \sin(\omega_d t - \varphi) = e^{-\alpha t} K \sin[\omega_d(t - t_\varphi)] \quad (1)$$

For full-bridge serial resonant converter supply with square voltage in [13], [14] is derived dependence on phase angle from damping and resonant circle frequency. This dependence is given with (2).

$$\varphi = \arctg \left(\frac{\sin(\pi \frac{\omega_d}{\omega_s})}{e^{\frac{\pi}{2Q} \frac{\omega_0}{\omega_s}} + \cos(\pi \frac{\omega_d}{\omega_s})} \right) \quad (2)$$

2.2 Calculated the maximal value on the output current

In full-bridge serial resonant converter supply with voltage $\pm U_{DC}$, the output current is given with (1). In [1], [2], [3] [4], in calculate on the output current of the full-bridge serial resonant converter with assumptions $\omega_0 \approx \omega_d \approx \omega_s$, $i_L(0^+) = 0$ and $u_C(0^+) = 0$ the phase angle, the maximum voltage of the capacitor U_{Cmax} and the constant K are :

$$\varphi = \arctg \left[\frac{\omega_0 L}{R} \left(\frac{\omega_s}{\omega_0} - \frac{1}{\omega_s \omega_0 LC} \right) \right]$$

$$U_{Cmax} = U_{DC} \frac{1 - e^{-\frac{\pi}{2Qx}}}{1 + e^{-\frac{\pi}{2Qx}}}, \quad K = \frac{2}{1 - e^{-\frac{\pi}{2Qx}}} \frac{U_{DC}}{\omega_s L} \quad (3)$$

With (3) the maximum voltage of the capacitor U_{Cmax} and the constant K are calculated in a small band around the resonant frequency and in calculated not taken to consideration the impact of the phase difference.

In this paper, first in calculation of the current in wide band around the resonant frequency for the phase angle we used above derivation exact equation (1) from [13], [14]. The second should be calculated the value constant K in this wide band. Determination of the constants K for the steady state solution can be done using two border conditions for this time interval, i.e. di/dt , $t = 0$ and di/dt , $t = T_s/2$. The voltage of the coil L is:

$$u_L(t) = L \frac{di(t)}{dt} = -LK\alpha e^{-\alpha t} \sin(\omega_d t) + LK\omega_d e^{-\alpha t} \cos(\omega_d t) \quad (4)$$

for $t = 0$

$$u_L(0) = L \frac{di(0)}{dt} = LK\omega_d \quad (5)$$

for $t = T_s/2$

$$u_L\left(\frac{T_s}{2}\right) = L \frac{di\left(\frac{T_s}{2}\right)}{dt} = -LK\alpha e^{-\alpha \frac{T_s}{2}} \sin\left(\omega_d \frac{T_s}{2}\right) + LK\omega_d e^{-\alpha \frac{T_s}{2}} \cos\left(\omega_d \frac{T_s}{2}\right) \quad (6)$$

$$\omega_d \frac{T_s}{2} = \frac{\omega_d}{\omega_s} \pi, \quad \alpha \frac{T_s}{2} = \frac{\alpha}{\omega_s} \pi \quad (7)$$

with this in (6) are obtained

$$u_L\left(\frac{T_s}{2}\right) = L \frac{di\left(\frac{T_s}{2}\right)}{dt} = -LK\alpha e^{-\frac{\alpha\pi}{\omega_s}} \sin\left(\frac{\omega_d}{\omega_s} \pi\right) + LK\omega_d e^{-\frac{\alpha\pi}{\omega_s}} \cos\left(\frac{\omega_d}{\omega_s} \pi\right) \quad (8)$$

On the other hand, at the series resonant circuit, when the current passing from 0^- in 0^+ in the moment $t = 0$, the voltage of the coil is:

$$u_L(0) = u_{Lmax} = U_{DC} - U_{Cmin} = U_{DC} + U_{Cmax} \quad (9)$$

From (5) and (9) for the constant K are obtained:

$$K = \frac{U_{DC} + U_{Cmax}}{L\omega_d} \quad (10)$$

In the moment $t = T_s/2$ when the current passing from 0^+ in 0^- , the voltage of the coil is:

$$u_L\left(\frac{T_s}{2}\right) = -u_{Lmin} = -(U_{Cmax} - U_{DC}) \quad (11)$$

From (6) and (11) for the constant K are obtained:

$$K = \frac{U_{Cmax} - U_{DC}}{L \left[\alpha \sin\left(\frac{\omega_d}{\omega_s} \pi\right) - \omega_d \cos\left(\frac{\omega_d}{\omega_s} \pi\right) \right] e^{\frac{\alpha\pi}{\omega_s}}} \quad (12)$$

with

$$Q = \frac{\omega_0 L}{R} = \frac{1}{\omega_0 C R}, \quad \alpha = \frac{R}{2L}, \quad \omega_0 \approx \omega_d \neq \omega_s, \quad x = \frac{\omega_s}{\omega_d}$$

as and (10) and (12), can be determined the maximum voltage U_{Cmax} of the capacitor C , i.e.:

$$U_{Cmax} = U_{DC} \frac{\left[\alpha \sin\left(\frac{\pi}{x}\right) - \omega_d \cos\left(\frac{\pi}{x}\right) \right] e^{\frac{\pi}{2Qx}} + \omega_d}{\omega_d - \left[\alpha \sin\left(\frac{\pi}{x}\right) - \omega_d \cos\left(\frac{\pi}{x}\right) \right] e^{\frac{\pi}{2Qx}}} \quad (13)$$

With used on (13) and (10), after a certain number of transformations for the constant K are obtained:

$$K = \frac{2U_{DC}}{L \left[\omega_d - \left[\alpha \sin\left(\frac{\pi}{x}\right) - \omega_d \cos\left(\frac{\pi}{x}\right) \right] e^{\frac{\pi}{2Qx}} \right]} \quad (14)$$

With the expressions (13) and (14) are determined the maximum voltage U_{Cmax} of the capacitor and the constant K in wide band around resonant frequency at the serial resonant converter.

From (13) and (14) with substituting $\omega_s = \omega_d$ are obtained the expressions, (3), for the maximum voltage of the capacitor U_{Cmax} and the constant K given in [1].

The maximum current of the converter is for $t = T_s/4$ and she can be calculated with used on (1) and (14), i.e:

$$I_{max} = K e^{-\alpha \frac{T_s}{4}} = \frac{2U_{DC}}{L \left[\omega_d - \left[\alpha \sin\left(\frac{\pi}{x}\right) - \omega_d \cos\left(\frac{\pi}{x}\right) \right] e^{\frac{\pi}{2Qx}} \right]} e^{-\alpha \frac{T_s}{4}} \quad (15)$$

With used (1), (2), (14) and (15) for the output current of the serial resonant converter in wide band are obtained:

$$i(t) = \frac{2U_{DC}}{L \left[\omega_d - \left[\alpha \sin\left(\frac{\pi}{x}\right) - \omega_d \cos\left(\frac{\pi}{x}\right) \right] e^{\frac{\pi}{2Qx}} \right]} e^{-\alpha t} * \sin \left[\omega_d t - \arctg \left(\frac{\sin\left(\frac{\pi}{x}\right)}{e^{\frac{\pi}{2Qx}} + \cos\left(\frac{\pi}{x}\right)} \right) \right] \quad (16)$$

In (16) the of the output current of the serial bridge converter is calculation in relation to the deviation of the switching of damping frequency in a wide band around the resonant frequency.

In the Fig. 4 is shown graph of the maximum voltage of the capacitor U_{Cmax} obtained with (13) with RLC values $R = 0.24 \Omega$, $L = 26.5 \mu H$ and $C = 26.6 \mu F$.

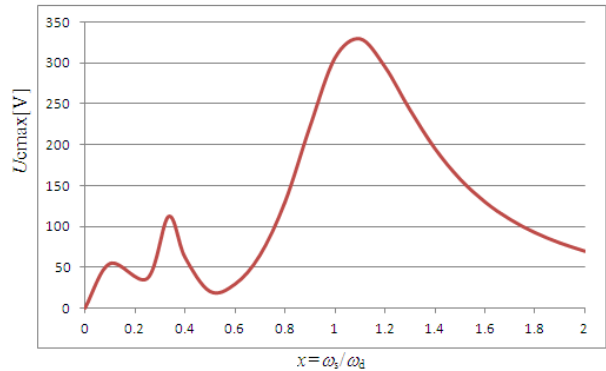


Fig. 4. Graph on the maximum voltage of the capacitor U_{Cmax} obtained with the exact equation (13).

In Fig. 5 is shown graph of the maximum output current of the converter for $t = T_s/4$ obtained with (15).

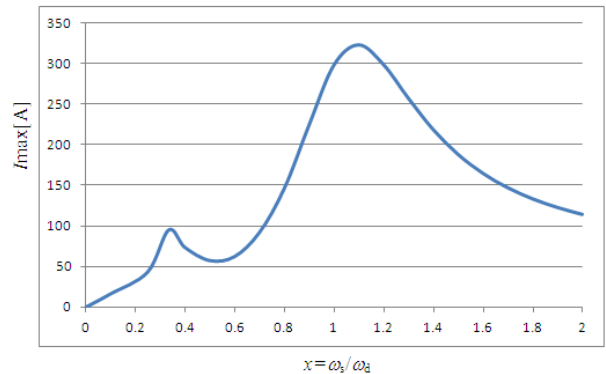


Fig. 5. Graph of the maximum output current of the converter I_{max} obtained with the exact equation (15).

3. Experimental results

A check of the theoretically derived equations in the preceding chapters is made using the full-bridge IGBT converter who operates in mode on the induction heating furnace with nominal output power converter from 15 kW and resonant frequency 5.994 kHz. In the Fig. 6 is shown control module on this converter.

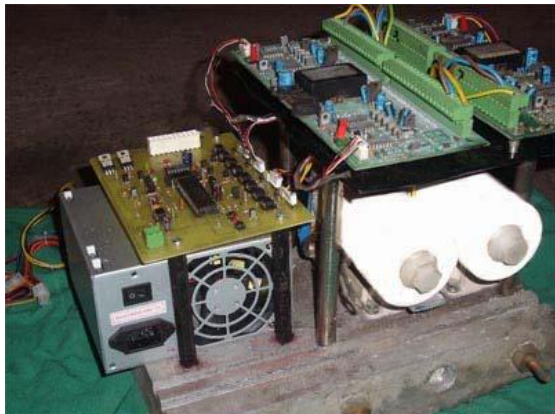
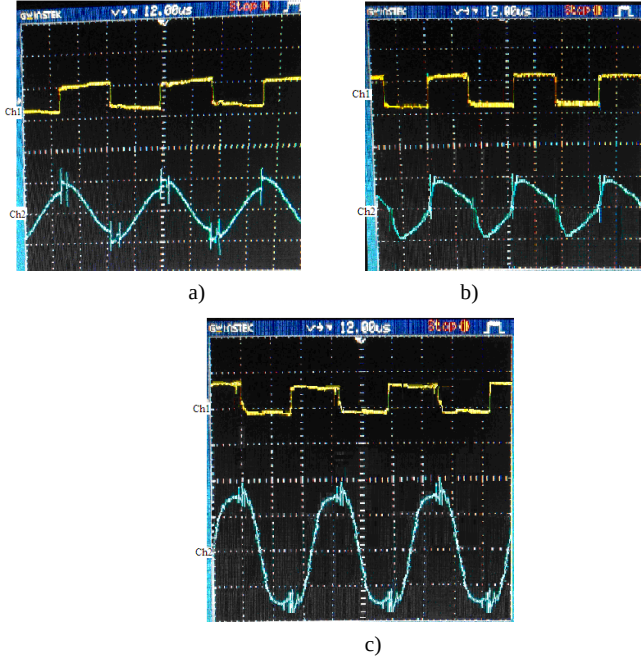


Fig. 6. The control module with IGBT drivers and IGBT transistors.

It is a serial resonant converter with a RCL load mentioned above. Resonant frequency is 5.994kHz. In the Fig. 7 is given wave form the on output converter voltage and current a) on a frequency 5,92 kHz, smaller from resonant, b) on the resonant frequency 5.994 kHz and c) at a higher frequency 6,15 kHz than the resonant.

In the Table I is given values on output converter voltage and current on wave form from Fig.7.



Ch1=100V/div, Ch2=300A/div, time=50μS

Fig. 7. Wave form the output converter voltage and current a) with a frequency smaller, b) at the resonant frequency and c) at a higher frequency than the resonance.

Table I: Values on output converter voltage and current on wave form from Fig.7.

f_s	effective value	
	U_o [V]	I_o [A]
5,92 kHz	55,60	244,00
6,00 kHz	56,10	247,20
6,15 kHz	55,70	244,00

In the Fig. 8 is given wave form the on output voltage and current of switching frequency $f_s = 0,5 f_0 = 2\,979$ Hz, obtained with simulation in PSpice [16]. (a) and with an experiment (b).

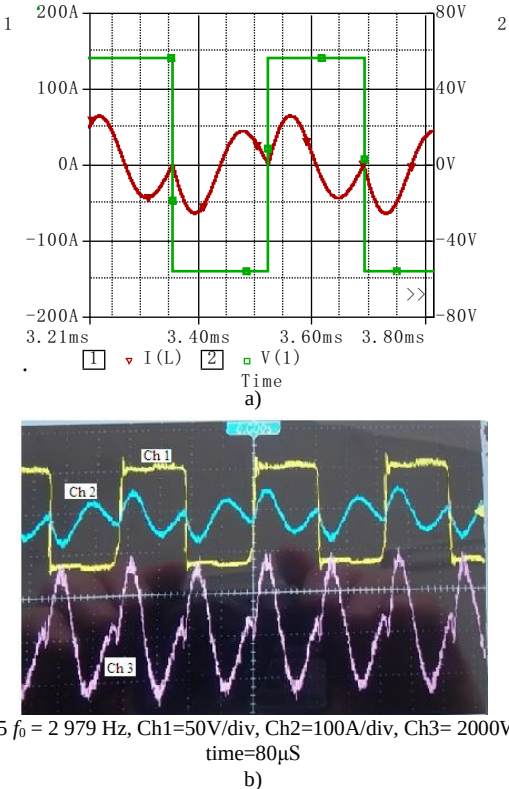


Fig. 8. Wave form on the output voltage and current of switching frequency $f_s = 0,5 f_0 = 2\,979$ Hz, obtained with: a) simulation in PSpice and b) with an experiment.

In Fig 8 on the channel 1 is given wave form on the output voltage, channel 2 is wave form on the output current and channel 3 is output converter active power.

3. Analysis of the results

From Fig. 5 we can see that the maximum value of the output current of the converter $I_{\max}$ according to the exact equation (15) is highest value for $x = 1.1$. Also and here for the values on $x < 0.6$ the maximum value of the output current has significant oscillations and for $x > 1.1$ this current decline with lower slope.

From Fig. 5 and Fig. 7b can see that for $f_s/f_0 = 1$, obtained is maximum current around 300 A with exact equation (15), as and with experimental results. For switching frequency above resonance $f_s/f_0 = 1.1$, the current has a greater value around 320 A.

Also from Fig.8 can see that for the frequency $f_s = 0,5 f_0 = 2\,979$ Hz maximal current value is around 60 A and it is the same current value of the graph of Fig. 5 obtained by the equation (15).

4. Conclusion

In this paper for full-bridge converter with serial resonant circuit, analytical are derived exact general equations for dependencies of the maximum voltage of the capacitor and the maximum value of the output current. This equations giving dependences on this parameters from the deviation on the switching from damping frequency in wide bands around resonant frequency. Derived expressions can be used for controlling of the full-bridge serial resonant converter. The results of the experimental testing are close to the values of the parameters obtained by the derived equations.. From these general equations can be obtained the equations for the case when $\omega_s \approx \omega_d \approx \omega_0$.

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ANALYSIS OF OPPORTUNITIES FOR DEVELOPMENT OF BULGARIAN INDUSTRIAL MANUFACTURING

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Abstract: This publication analyses opportunities for development of Bulgarian industrial manufacturing in conditions of dynamic self-changing competitive environment during the period 2015 – 2018. A comparative analysis is done for different industrial sectors with purpose to determine the trends in their development and to identify the opportunities for improvement of their production activity. Actual statistical data are used and different methods for the existing information analysis. The specific of development in the leading sectors in Bulgarian economy are identified. In addition, a comparative analysis is implemented as well as a classification of different industrial sectors on the base of Index of industrial production is created. The results show that the realized production of Bulgarian industrial enterprises during the considered period increase. This is a reason to search favourable opportunities for their further sustainable development and competitive location on the internal and external markets. Some fundamental problems and barriers in the industrial enterprises are considered, that obstruct the fast temps of their developments and are presented some appropriate decisions. The current publication put the beginning of a more depth investigation of the effectiveness of the industrial enterprises, their capacity utilization, as well as the development and introduction of different types of innovation decisions that will be implemented during the next two years in the range of a doctoral thesis in the field of the same problematics and researching analogical problems in the more comprehensive aspect..

Keywords: INDUSTRIAL MANUFACTURING, INDEX OF INDUSTRIAL PRODUCTION, FAVORABLE OPPORTUNITIES, SUSTAINABLE DEVELOPMENT

1. Introduction

This analysis provides information on the status and opportunities for development and improvement of Bulgarian industrial production by industry. The aim is to identify the leading industries in recent years and to analyze the opportunities for their sustainable development and improvement. The main sectors with potential for development are constantly being researched, but in general the research on this problem is not done in depth, which is the reason for this research. The analysis is made in three parts.

The first part looks at the impact of the changing economic environment on individual sectors based on industrial production index. The trends in development of the industrial sectors during the period 2015÷2018 are presented, and a comparative analysis is made.

The second part deals with the main key points regarding the investment activity of industrial enterprises, namely the realized investments in industry and their future investment plans.

The third part looks at the main trends in the economic conjuncture of industry among the main industrial sectors. Major barriers have been identified and the most influential barriers to business development have been classified.

2. Trends in the development of the industrial sectors in Bulgaria

Bulgarian industry consists mainly of: mining, processing, production and distribution of electricity and heat and gas. There are some key economic indicators measuring, analyzing and representing the development and trends of the industry in Bulgaria. The first part analyzes several major sectors of the manufacturing industry. The subject of analysis is the sectors classified according to the Classification of Economic Activities (NACE.BG-2008):

- Manufacture of computer and communication equipment, electronic and optical products;
- Manufacture of general and special purpose machinery and equipment;
- Manufacture of cars, trailers and semi-trailers;

The main indicators by which the above industries are compared are:

- Value added;
- Industrial production index;

- Domestic and foreign trade;

- Employees;

Manufacture of computer and communication equipment, electronic and optical products

In 2016 the manufacture of computer, electronic and optical equipment contributes 3% to the value added created by the manufacturing industry, reducing its share by 0.3% compared to 2015.

Manufacture of computers, electronic and optical products "consists of the production of: electronic components and printed circuits, computer equipment, radio, television and telecommunications equipment, consumer electronics, measuring instruments, clocks, electromedical apparatus, optical instruments and photographic equipment, magnetic and optical media, etc. Made by 437 companies.[4]

In 2017 the production of computers, electronic and optical products increased by 21% compared to the previous year. In 2018. The largest increase since 2005 was reported. with nearly 44%. Since 2004. there is an upward trend in production. Since 2008. exports of computers, electronic and optical products are on a steady upward trend. The highest export growth was recorded in 2011. and 2015 or 16% y / y. The overall increase in exports of computers, electronic and optical products in the period 2008-2017. is 113%, and in 2017 C26 exports account for 3.7% of the country's total exports. The number of employees since 2015 increased by about 15% for the period 2015÷2018. or nearly 1.5 thousand more were hired, compared to 2015 (8.4 thousand). [3]

Manufacture of general-purpose machinery and equipment

In 2016 manufacturing of general and special purpose machinery and equipment contributes 6.4% to the value added created by the manufacturing industry. The production consists of the production of turbines and engines, hydraulic pumps, compressors, fittings, bearings, gears, furnaces and burners, lifting machinery, office equipment, tools, refrigeration and ventilation equipment, agricultural machinery, metalworking machinery, metallurgy equipment. and foundry and other industrial machinery. There are 1,026 companies. In 2016 the production of general and special purpose machinery and equipment increased by 2.2%, and in the next 2017. 14.8% increase in production was reported. In 2018. the index reached a value of 119 points, which is a 19% increase for the period 2015÷2018. [4]

Exports of general and special purpose machinery and equipment have been on an upward trend since 2012, with the highest growth being in 2011, or 52%. The total export growth in the period 2015÷2018, is 19%. In 2017 exports of articles of other non-metallic minerals accounted for 6.9% of the country's total exports. The sector's employees have been slowly increasing since 2015. Since 2015÷2017, the average annual decrease is 0.3%. The total number of employees increased by almost 1.9 thousand people during the whole period. [3]

Manufacture of cars, trailers and semi-trailers

In 2016 the manufacture of cars, trailers and semi-trailers accounted for 3.4% of the value added created by the manufacturing industry, reducing its share by 0.2 percentage points compared to 2015. [4]

Automobile production is one of the priority high-tech sectors for attracting foreign investments in Bulgaria, with great potential for development of exports, employment and regional economic activity. The industry is strategic for the economy of the country with a long-term perspective, but at the same time, for its successful development requires a number of factors - infrastructure, specialists and prerequisites for development.

Automobile production in the country has established traditions and experience, a suitable basic infrastructure for the needs of the manufacturing industry has been developed. In recent years, the automotive sector in Bulgaria has seen a significant upswing and has been the subject of increased interest from potential new investors and suppliers of car components.

The average change in the industrial production index in 2016 and 2017, is 10.4% and 7.6% respectively. As for the period 2015-2018, the motor vehicle manufacturing index increased by almost 37 percentage points. Exports of cars, trailers and semi-trailers are also increasing, with a record growth of 60.5% reported in 2010. In 2014 and 2015 industry exports increased by 18% and 28% respectively. In the following years, a drastic decrease in the export from the branch is observed compared to the total export of the country. [4]

There are one car assembly plant in the country, and 126 companies manufacturing automotive components as subcontractors to leading automotive companies. Employees in the industry have seen an increase since 2015 since 2015÷2018, the average annual increase is 12.4%. For the whole period the total increase in the number of employees is close to 3.5 thousand people.

Based on information on changes in industrial production indices in 2015-2018. The author analyzed and systematized the dynamic changes in the industrial production index of the aforementioned industries. Each of the branches is compared to the others, according to the author's average index of industrial production, the following classification is made (Table 1) [4]

Table 1: Classification of industrial sectors by average value of industrial production index (2015-2018).

№	Industries	Average value of the Industrial Production Index (2015÷2018)
1	Manufacture of computer and communication equipment, electronic and optical products	114.9
2	Manufacture of cars, trailers and semi-trailers	110.3
3	Manufacture of general-purpose machinery and equipment	107

3. Investment activity in industry - key features

This part of the analysis uses data from the NSI Investment Business Surveys, and the monitoring collects information on the investments made and the investment plans of the enterprises. Managers are interviewed twice a year - in March and October, with questionnaires having different content.

About 3,800 enterprises in the industrial sector are interviewed. The results of the survey conducted by industrial enterprises for the period 2015÷2018. The following conclusions about the development and investment activity in the industry in Bulgaria can be analyzed, deduced and marked: [4]

The largest relative share in the expected investments is concentrated in the increase of the production capacity, formed overall for the country. Data show that in 2015, The value of investments for increasing production capacity is the lowest - 29.1%, as in 2016. It increased by 6.1% and reached its highest value - 35.2%. Over the next two years, investments fall to 33.3% of the total investment in industry.

Second is investment in replacement of worn-out equipment. There is a trend of increasing investments for replacement of worn out equipment - in 2015, the investment in the represented production group is about 29.3%, and at the end of 2018, increased to 31.3%.

The downward trend in investment is also observed in the next production group - mechanization and automation of the existing production process and introduction of new production technologies - from 24.2% in 2015 to 20.5% at the end of 2018. Investments related to environmental protection, security measures and others also tend to decline. From 17.4% in 2015 to 14.9 at the end of 2018. Investments in the production of non-durable consumer goods decreased (from 20.4% in 2015 to 18.7% at the end of 2018), while investments in the production of intermediate goods increased by 11% in the period 2015-2018 and reach 42.9%. [3]

One of the factors influencing the decisions for investments in the Bulgarian industrial production in the next year, namely the demand for production has the lowest value in 2015. - 47,2% and the highest value was reported at the end of 2017 (50.4%). In 2018, a decrease of about 3.2% was registered.

In the distribution of expected investments by major production groups for the period 2015-2018, there is a decrease in the expected investments in the energy and water-related industries - for 2015, they are about 33.7%, and at the end of 2018, they reach 21.7%. The growth of expected investments marks the production of intermediate goods - by 31.9% (in 2015) increased by 11% and recorded a value of 42.9% (in 2018).

The distribution of planned investments by major production groups for the period 2016 - 2019 outlines a trend to reduce planned investments in energy and water-related industries - from 39.4% of planned investments for 2016 to 29.3% in 2019. The production of intermediate goods marks the highest growth of planned investments for 2017 (40.85), with the lowest value in 2016. (32.4%). An increase in the value of planned investments is expected in the production of non-durable consumer goods as well as in the production of investment goods.

In terms of R&D expenditure by funding source and sector, the following classification can be made:

For the period 2015÷2018, there is a lasting trend of increasing R&D investment by enterprises. The same conclusion can be made regarding the investment of R&D by the public sector and non-profit organizations developing in the industrial industry. On the other hand, the tendency to reduce the participation of foreign investments in improving R&D can be highlighted.

According to the NSI, industrial enterprises are classified into several groups based on employees. (Table 2)

Table 2: Classification of industrial enterprises by number of employees according to NSI

№	Classification of enterprises by number of employees
1	1 to 9 employees
2	10 to 49 employees
3	50 to 249 employees
4	250 to 499 employees
5	500 or more employees

The trend observed can be outlined as follows:

R&D expenditure in industry by size of enterprise for the period 2015÷2018 has been steadily reduced. Only companies with between 10 and 49 employees increase their costs related to improving and improving their R&D activities. All other aforementioned companies concentrate their strategies and policies on almost double the cost reduction. [4]

4. Business trends in industrial production. Analysis and classification of major barriers to industry development.

This part of the analysis presents and analyzes the business trends or so-called Business Surveys (NSI) surveys. Unlike traditional statistical surveys, business trends present information of a largely non-quantitative, verbal nature. They seek input from economic agents (business managers and consumers) about current or expected changes in a particular set of economic variables or

estimates of the current level of these variables. In short, business surveys provide important and different information than traditional statistics, namely information about the prevailing, most widespread opinion about the present or future behavior of an economic phenomenon. Future information is an extremely important feature of business trends, which in turn makes them an extremely good source for early warning systems for changes in the economy. [4]

Although business surveys do not collect numbers but views, it is logical to think that opinions about increased production, exports, etc. for example, it weighs more on a large enterprise than the same opinion on a small industrial enterprise. This is due to the generally accepted fact, namely that the contribution to the economic activity of different organizations (enterprises, companies) is different and directly related to their size (scale or market share). From an industry perspective, each industry's contribution to economic activity is proportional to the added value it brings to the economy.[1]

In order to use and analyze business survey data (through a survey) as short-term economic indicators, it is important to translate non-quantitative responses into quantitative indicators. The balance of views is most appropriate.

In Fig. 1 presents the change of the present business situation of the industry for the period from 2015 to 2018. The balance of opinions indicator reached the lowest value of 21.6% (in April 2016) and the highest - 41.8% (in July 2018). The trend towards the present business situation in the industry is characterized by gradual development. [4]

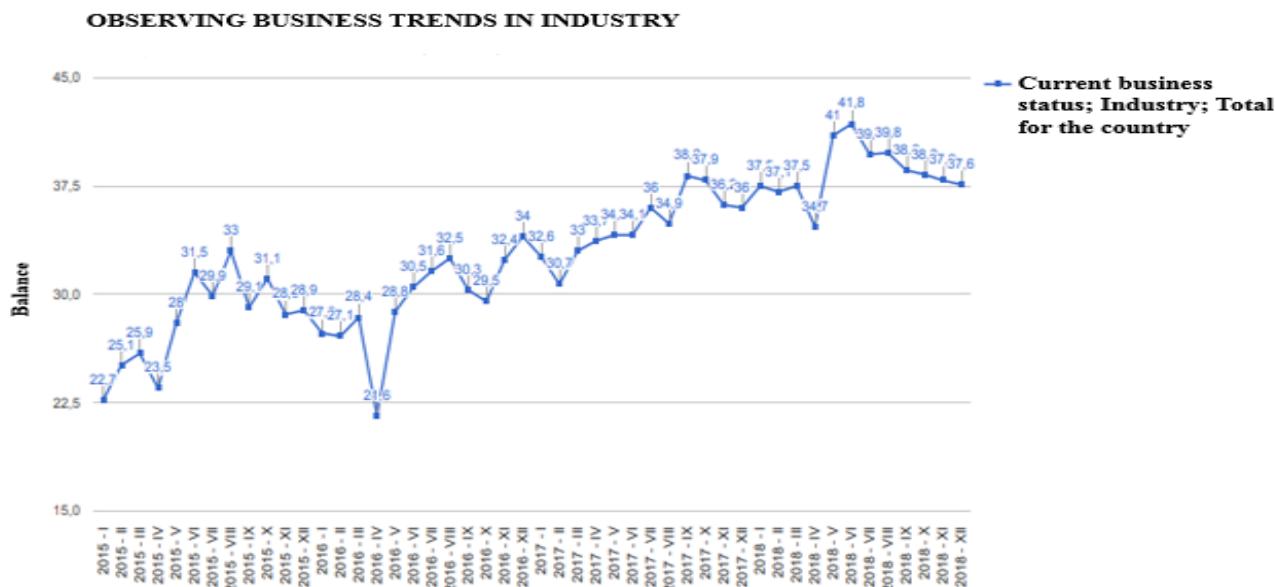


Fig. 1. Changes in the business situation of the industry for the period from 2015 to 2018.

The following factors are an integral part in forming the so-called business climate in industry: [4]

- Uncertain economic environment;
- Insufficient demand from the country;
- Weaknesses in economic legislation;
- Insufficient demand from abroad;
- Shortage of materials and / or equipment;
- Financial problems;

- Labor shortages, including skilled labor;
- Competitive imports;
- Energy shortage;

Among the factors influencing the economic situation of the industry are the current production activity, the level of orders and the level of finished goods stocks.

In this part of the analysis, an attempt was made to classify the "Most serious obstacles to the development of industrial production".

According to the analysis of data from the NSI Business Information Surveys for 2015 In the first three places, the following factors are the most serious obstacles to the development of business (industry): uncertain economic environment, insufficient demand from the country and weaknesses in economic legislation. With less influence are indicated - shortage of materials and / or equipment, shortage of labor, including qualifying. With little influence on the business situation of the industry, the factors are competitive imports and energy shortages.

The trend for the most influential factors continues in 2016. in the first place are the uncertain economic environment and the insufficient demand from the country. Factors such as labor shortages, including skilled labor and competitive imports, all increase their negative impact on industrial production. With a less significant impact are again a shortage of materials and / or equipment and a shortage of energy.

In 2017 the so-called 'most serious impediments to the development of industry' classification occupy the forefront - an uncertain economic environment and labor shortages, including skilled labor. The factors affecting the insufficient demand from the country and abroad, the weaknesses in the economic legislation, the competitive import, the financial problems of the industrial enterprises are characterized by the weak influence and lastly the shortages of materials and / or equipment and the energy shortage are again mentioned. .

The level of finished goods stocks also provides information on the development of the economic situation of the industry. At the beginning of 2015. at the level of stocks of finished industrial production is positive - there is a surplus. Over time, there is a trend of shortage of stocks of finished industrial production by May 2018, when a positive value of this indicator is taken into account. The surplus of finished products is observed by the end of 2018.

5. Conclusion

The stability, development and refinement of each industrial sector plays a particularly important key role in enhancing economic growth, job creation, promoting the expansion of production capacity of Bulgarian industrial enterprises, with both export and import projections.[2]

In this publication, a small fraction of the sectors that build and describe such a complex and dynamically developing Bulgarian industrial industry are presented and analyzed. The focus of the analysis is on selected industries. As a result of this study, some scientifically sound guidelines for their future development are offered:

1. Optimization of the organizational structure of industrial enterprises;
2. Creating new jobs and investing in staff training ;.
3. Technological modernization and creation of high value added products.

4. Modernization of outdated infrastructure and expansion of the transport network in the country.

5. Introducing a vision for the development and functioning of the industrial sectors.

6. Increasing the cost of R&D, as it is a factor that has a positive impact on the economic growth and competitiveness of enterprises.

7. Attracting more foreign direct investment as a major source of economic growth and a factor in achieving and improving the competitiveness of industrial enterprises.

8. Increasing the competitiveness of industrial production by increasing the degree of resource efficiency.

9. Stimulating technological innovation.

10. Stimulate the creation of new innovative products.

11. Strengthening the Business - Academic - Country.

The prosperity of the Bulgarian industrial production goes hand in hand with the macroeconomic situation and the business climate in the country, with the introduction of incentives for attracting foreign investors, improving the conditions for investment realization, expansion and modernization of infrastructure, more targeted and specific policy, aimed at improving the quality of education in the country and the availability of well-prepared and skilled workforce. A broader analysis of these factors affecting the industry is the subject of a follow-up study.

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IMPROVING THE CLASSIFICATION OF STRATEGY OF INNOVATIVE ACTIVITY OF THE ENTERPRISE

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Anotation. The classifications of innovation strategy of industrial enterprises are investigated: their advantages and disadvantages are determined. Classifications of innovation strategy of industrial enterprises are improved. Classification features, types of strategies of innovation activity of industrial enterprises are characterized. The expediency of using a certain innovation strategy of industrial enterprises is substantiated.

KEYWORDS. Strategy, innovation activity (IA), characteristics, types, classification, factors, characteristics, improvement, indicators, evaluation.

Analysis of recent researches and publications. Most researchers considered the classification of the innovation strategy only and did not investigate the classification features of the strategy of innovation activity, as well as in the mentioned classifications of innovation strategies, to a greater extent, the need to improve the activities of enterprises, the feasibility of using scientific and technological developments are taken into account, the quality of products, the production of a new product are emphasized, the needs of the consumer, evaluation of factors of the macro environment are considered, but there are no signs of innovation activity of industrial enterprises, the possibility of influencing the threats of the internal and external environment, resource availability, investment development, the long-term nature of the strategy, the sphere of activity and sector specificity of the enterprise, the direction of economic development.

Chubay V.M. conducted a thorough analysis of approaches to the classification of innovation strategy. [3, p. 6-7; 4, c. 349], in his study he distinguished a group of classification features: by way of satisfaction of existing consumer needs; by the areas of innovation; by location of the enterprise; in accordance with the objectives of the enterprise; depending on the position of the company on the market; depending on the stage of the life cycle and the level of competitiveness; by way of applying innovations; on the level of attractiveness of the market; by the level of efficiency of all types of activity of the enterprise. The advantage of the given classification is that the author takes into account the peculiarities of the activity of the enterprise, its divisions, the specifics of the process of manufacturing each individual product unit, defines the main objectives of the activity and the ways of achieving them, but the influence of risks on the development of the enterprise, the direction of innovation activity, the relationship between investment and innovation development of the industrial enterprise are not evaluated.

Another author Fedulova I.V. [1; 2, p. 126] in her study carried out a deep analysis of existing approaches to the classification of innovation strategies, considered the features of strategy development, analyzed the factors of influence on their formation. The author, based on the results of the research, identified a group of classification features of the innovation strategy, which include: the degree of novelty of the use of research (active, passive); by the level of accessibility of the innovative model (open, closed); depending on competitive behavior (patiences, violations, commutants); on the direction of development of the enterprise (market, commodity, production, management); depending on the development of technologies (availability of technologies, lack of innovation, financing of development, licensing); by the level of competitive positions (cost reduction, diversification, leadership). The given classification allows us to choose the innovative strategy that will help achieve the established goals of the activity, introduction of innovative technologies, crowding out competitors, and setting up innovative activities.

At the same time, in the given classifications there are some contradictions, inaccuracies and differences, they are not adapted for the activity of industrial enterprises, therefore we

consider it appropriate to supplement the classification of strategies of innovation activity of enterprises.

Results. In accordance with the results of the analysis carried out, we have identified the existing classification features and defined the essence of the supplemental classification (Table 1).

The table. 1 shows that the correct strategy gives a chance to establish the innovation activity of the enterprise through the successful construction of a business model, increasing the efficiency of introducing innovations, investment activity, improving the production process and entering new markets.

On the basis of the development of the enterprise, the competitive position and the level of investment activity, the following strategies have been formed: rapid growth - is characteristic for enterprises with a high level of economic development, protection from the influence of factors of the environment, which not only develop new technologies, but also introduce them into production, reduce the use of human resources, produce entirely new products, and not an analogue of any product, have energy-saving production; moderate growth - used by enterprises that have undergone the stage of basic development, are trying to implement innovations, produce products with new characteristics, provided with investment resources; reduction - there is a decrease in the volume of production of quality products, the pace of innovation is decreasing, but if there are investments, there are opportunities for improvement of activity; a rapid decline in production volumes - production is unprofitable, there is a decrease in demand for manufactured goods in connection with the appearance of analogues of lower price and higher quality, output only for the domestic market, limited range of consumers, reduction of competitiveness of the goods, absence of application of innovative technologies, deterioration of indicators of economic development, indicating the expediency of making adjustments to the management system of the enterprise, change of organization, planning, control over innovation activity.

Depending on the intended purpose of the innovation activity and the sphere of operation, the following types of strategies are defined: at the level of separate units - updating the range of products due to the needs of consumers, directing innovations only in separate departments, narrow specialization of the enterprise, expectations of rapid growth of profit; at the enterprise level - aimed at a comprehensive upgrade of obsolete equipment, the development and implementation of innovative technologies, the monitoring of constant changes in the development of researches, acquirement of licenses, personnel training; at the state level - production for the needs of the state, export of goods, distribution of goods in the foreign market, gaining competitive positions, receiving state support, modernizing existing technologies; at the level of the region - updating of the main types of activity, introduction of nanotechnologies, resource-saving technologies, high-tech development, raising the level of welfare of the population, environmental protection, meeting the needs of consumers, social, economic, financial development of the region and support of enterprises; at the level of a separate branch - production of products for the needs of agriculture, food industry, energy, transport, manufacturing goods depending on the needs of

the industry, increasing the volume of orders, establishing contacts with customers, finding new customers and new suppliers, the

application of information technology, the introduction of technologies in a certain area of activity.

Table 1 Classification of the strategy of innovation activity of the enterprise

№	Classification indication	Kind of innovation strategy	Characteristics of the classification indication
1.	Level of enterprise development, competitive positions and level of investment activity	growth at a fast pace; moderate growth; reduction; a rapid decline in production volumes	Determines the company's ability to innovate, increase the pace of investment activity, assess the level of security of investment capital, allow the organization of business processes of the enterprise, increase the level of competition.
2.	Depending on the purpose of the IA and the sphere of functioning	at the level of separate departments; at enterprise level; at the state level; at the regional level; at the level of a particular industry	They are used because of the need to assess the list of main tasks of the enterprise, industry orientation, the definition of the market niche and the needs of consumers, the need to apply several strategies, depending on the scale of activity, geographical location.
3.	The ratio of the directions of the IA and the objectives of the enterprise	basic (investment); development (growing); professional; reduction	Allows you to assess the attractiveness of the market, win leading positions, outline the prospects of functioning, the feasibility of introducing innovations and the production of new products.
4.	The effect of innovative activity	financial; environmental protection; production; investment	Implementation of these strategies will allow to fulfill the tasks, evaluate the effectiveness of the chosen strategy, make adjustments in line with changes in the needs of the enterprise, and assess the level of investment activity.
5.	The degree of riskiness of innovation	high-; medium-; moderately risky	Estimation of the level of risk impact on the development of enterprises, the possibility of innovation activities under the conditions of the threat of the environment.
6.	Depending on economic expediency	maximizing profits; minimize risks; resource availability; R & D; leading positions; social security; economic security	They are used to ensure an increase in the efficiency of the enterprise, increase financial indicators, which will allow to evaluate the prospects of innovation and how to manage innovative development.
7.	The level of potential of enterprise IA	stable development; development of innovation activity; avoidance of risks; combined	The existing level of financial performance of an enterprise contributes to the choice of strategy depending on the assessment of the possibilities for further development, investment potential and IA, which will allow to achieve the established goals.
8.	Accomplishment of innovative activity, realization of innovation	first-introduction; traditional; the strategy is focused on the introduction of innovations; maintaining a benchmark for the use of innovative technologies	Assist to evaluation the effectiveness of functioning of traditional business, assessment of threats of market environment, determination of expediency of investment to the development of innovation, substitution of production spectrum, attraction of competitors technologies, change of organization form.

Note: Designed by the author on basis [3, 4]

On the basis of the ratio of directions of innovation activity and goals of the enterprise activity, the following strategies were identified: basic (investment) - it is expedient under the condition of initial stages of enterprise development, production with using of outdated technology, insignificant amount of investment resources, but there are opportunities for improvement of performance indicators, introduction of innovation technology; development (growing) - the possibility of output for other industries by updating its characteristics, satisfying the needs of a wide range of consumers, increasing the level of competitiveness of products, sufficient amount of investment resources; professional - characteristic for enterprises with a high level of investment potential, production of qualitatively new products, the creation of new machines and equipment, innovative competitive products are produced in order to conquer new markets, production is provided with new equipment, economic development is increasing; reduction - is formed under the condition of increasing the influence of factors of the market environment on the innovation activity of the enterprise, the crisis situation, the growth of the number of competitors, the lack of opportunity to produce new products in connection with the increase in costs and causes the decline in production capacity, the transition to another kind of strategy or change in product range.

In accordance with the received effect from the implementation of innovation activities, the strategies were divided into: financial - coherence of the work of all departments of the enterprise, balanced decision-making, effective management system of the enterprise, the justification of the development of its own base of innovation, reduction of threats to the market environment; environmental protection - application of energy saving technologies, automation of production process, ecological compatibility of packaging, reduction of pollutant emissions, implementation of payments for pollution of the environment; production - replacement of manual labor on automated systems, modernization of equipment, improvement of staff qualification, reduction of raw materials and materials, search of new clients; investment - availability of sufficient resources for the purpose of development of innovation activities, directing funds for conducting research works, development of the spheres of enterprise activity, achievement of competitive positions in the market.

It should be noted that according to the degree of riskiness of an innovation strategies can be: high-risk, that is, the implementation of this strategy can cause the enterprise to be damaged, because there are no effective methods for combating risks, the introduction of innovations takes place at the level of their borrowing from competitors, increases the amount of costs, there is

a loss competitive positions in the commodity market; the medium risk is characteristic for enterprises that produce products with new properties, but are not convinced of the possibility of growth in demand for products and at the same time the possible improvement of the results of innovation activity as a result of meeting the demand of a certain circle of consumers; moderate-risk is a way of preserving competitive positions, introducing innovations in various spheres of activity, conducting research works, cooperating with foreign firms, developing intellectual potential, diversifying production, a prerequisite for the company to enter a new stage of innovation development.

Depending on the economic feasibility the strategies are divided into: the strategy of maximizing profit determines the directions of increasing the profitability of the enterprise, aimed at improving the management system, development and implementation of technological developments that will reduce the cost of servicing obsolete equipment; risk minimization defines measures, methods of combating identified risks, allows us to find out the list of threats to the external and internal environment; the availability of resources characterizes a sufficient amount of not only their own, but also attracted investment resources, which are the prerequisites for the IA; research and development aimed at development, use in practice of resource-saving technologies, attraction of innovations, monitoring of the dynamics of technology market development; leading positions ensures the preservation of competitive positions of the enterprise provided the production of quality products, the timely introduction of innovative technologies; social protection guarantees the creation of proper working conditions, the establishment of the atmosphere in the team, the application of various incentives for labor; economic security determines the company's readiness for economic development, the possibility of using innovations, aimed at the harmonious functioning of all units, increasing the stability of activities.

By the level of potential of enterprise IA, the following types of strategy were identified: the strategy of sustainable development is used by enterprises with favorable conditions of functioning, sufficient level of investment resources, available potential of successful innovation, reduction of the number of threats to the environment; the strategy of innovation development is possible provided that there is a free investment capital, the use of available technologies, the availability of competitive advantages, the ability of the enterprise to develop, attracting foreign investors; risk avoiding strategy is used by the enterprises with insufficient investment resources, low level of innovation development, but only when the profits cover costs; a combined strategy is a combination of several strategies and is appropriate on conditions that according to predicted data the business will flourish, and it will allow to assess the prospects of economic development of the enterprise.

By the necessity of the implementation of the IA and the accomplishment of innovations some strategies were determined: the before innovative strategy is used by the enterprise when it was decided that the use of innovation is inappropriate, does not threaten development and there is no need to attract investment resources, change in management structure. The implementation strategy is typical for the enterprises that see the use of innovation as a prospects for development, which will gain advantages over competitors, increase the attractiveness of products among customers, improve the production process. The traditional strategy is the direction of investments into traditional spheres of activity, use of proven innovative technologies, minimize the risks, lack of attempts to produce new products, improve product quality; the strategy focused on the introduction of innovations is used by enterprises that operate in the market for a long time, introduce several types of researches, produce innovative types of products of different types, follow the development of the technology market, force out competitors. A strategy to maintain a benchmark for the

use of existing technologies describes enterprises with a slower rate of attraction of innovations which make calculated management decisions, prefer proven technologies, change the way of doing business, finance research and development, covering the narrow consumer sector.

Conclusions. The classification is improved, which, in contrast to the existing ones, allows us to choose a more effective strategy and methods for its implementation in the process of forming the strategy, takes into account the specifics of the strategy implementation at industrial enterprises, the availability of sufficient resources, permits us to evaluate the possibilities for implementing the strategy, to form competitive advantages, to determine the required amount of investments for the development of innovation activity, all this makes it possible to assess the peculiarities of the implementation of the strategy, taking into account the potential of the enterprise, the level of its development, the target purpose of innovation activity and the sphere of functioning, the ratio of directions of innovation activity and goals of activity, the effect of innovation activity, the level of riskiness, economic feasibility, the need for innovation, and creates opportunities for achieving strategic goals, reducing the risks, assessing the economic effect, complex development.

The use of the above classification allows to find out the type, main features, advantages and disadvantages of each strategy, to select and evaluate the effectiveness of the strategy of innovation, to determine the possibilities of the enterprise, innovation and resource potential, the feasibility of using the strategy as a tool for improving the efficiency of the operation of the enterprise, the preconditions for economic development on conditions that there is a sufficient amount of investment resources.

In practice, most enterprises use several strategies for innovation activity in order to achieve their full development, consolidate competitive positions, and the possibility of a rapid transition from one type of strategy to another, since each type of strategy has a number of characteristics, benefits, and peculiarities of functioning that allows organizing the enterprise, promoting innovative transformations in all departments.

The IA strategy plays a significant role in the development of the enterprise and permits to solve a number of weighty problems and the main tasks. At the same time, it is impossible to implement one or another strategy of innovation activity if the enterprise is at the initial stage of its activity and only a general strategy is implemented. Only after the introduction of technologies, the establishment of the level of economic security at the enterprise there is an opportunity to use the strategy of innovation, which also depends on the economic, political situation in the country, the position of the company on the market, investment and innovation potential, equipment with modern outfit, type of products, methods of protection against threats, level of competition.

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Al MATRIX FGM HAVING 5, 15 AND 25 % B₄C_p REINFORCED LAYERS

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Abstract: Functionally graded materials (FGM) containing different amounts of B₄C particles within 4 layers in an aluminum matrix were produced and characterized. The layers contained B₄C particles at amounts of 0, 5, 15 and 25 volume %. In order to form the composite structure, pure aluminum (<10 microns), copper (1 micron) and B₄C powders (<10 microns) were utilized. After mixing, functionally graded materials were compacted and shaped in a rectangular cross sectional geometry, having 6.4 mm thickness, 12 mm width and 33 mm length, by cold pressing at 600 MPa pressure. The parts were pressureless sintered at 610 °C for 30 min in high purity nitrogen atmosphere. The properties of the FGM sample were compared with those of the sample which did not contain B₄C particles, and which contained 25% B₄C particles throughout the whole sample.

Microstructural examinations were performed by an optical microscope. 3- point bending tests were conducted by a universal testing machine. The sample that did not contain B₄C particles presented a 3-point bending strength of 380 MPa, whereas the sample that contained 25 % B₄C had a bending strength of 140 MPa. The FGM sample had a bending strength of 190 MPa. However, the failure of the FGM sample was composed of steps. The stepwise failure of the FGM sample was due to delamination and fracture of the layers containing 15 and 25 % B₄C. Microhardness values of each layer the samples were determined by Vickers micro hardness measurements.

Keywords: FUNCTIONALLY GRADED MATERIALS, ALUMINUM MATRIX, B₄C

1. Introduction

Continuous advancements in the modern industry have brought about the request for unconventional materials and properties. This necessitated a renovation of materials from their monolithic forms to composites, properties of which could be tailored as a function of their constituent's type and ratio [1-3].

Functionally graded materials (FGM) in a sense can be thought to be in the category of composite materials. They exhibit a graded structure and gradually changing properties, and they are constructed to provide a greater performance [1-3].

The graded structure of the FGMs can depend on variation in factors such as density, grain size, chemical composition or other physical properties. The change in the structure, brings about the variation in the properties, on an axis of the FGMs. The change in the structure or properties may be abrupt in passing from a layer to a subsequent layer, or it may be gradual. The gradual transition in the structure and properties eliminates the incompatibility that would otherwise take place in an abrupt transition [1-3].

The most common example on the benefits provided by the FGM structure is the elimination of thermal stresses. For example, in the combination of two dissimilar materials such as a metal and a ceramic, the thermal stress caused by the different amount of expansion of the joined materials leads to crack or delamination of the joint. Thus, a gradual change in thermal expansion coefficient, created by the FGM structure, could be useful to prevent the thermal stresses and delamination in the material [1-3].

Powder metallurgy, which involves the formation of articles by starting from their particles, has the advantage of microstructural and compositional control not only in the whole body of an article, but also as a function of position on an axis. It is a widely used technique which provides production with net shape. It is sometimes more economical and faster than other manufacturing methods. Therefore the formation of compositional gradients is mostly easier with powder metallurgy, than other production techniques. Formation of layers as thin as 1 mm is possible with this method by piling layers on one another [1,3-5].

In literature, B₄C, SiC, Al₂O₃ and TiB₂ have been used as reinforcement phase in aluminum matrix in FGM structure [2]. Centrifuge casting is utilized in most of the studies in literature on FGM [2].

In the study of Canakci et al. [4], Al-10%B₄C and Al-5%-10%B₄C FGMs were prepared by powder metallurgy. It was reported that hardness of the layers increased with increasing B₄C content.

In the present study, powder metallurgy was employed for formation of FGM which consists of layers having 5, 15 and 25 % B₄C reinforcement particles in an Al-%4Cu matrix.

2. Experimental Procedure

The unreinforced Al-%4Cu sample, sample reinforced with 25 vol.% B₄C having Al-%4Cu matrix and the FGM sample were produced by powder metallurgical techniques. The first layer of the FGM was unreinforced Al-%4Cu alloy. The other layers of the FGM were essentially individual metal matrix composites, having 5, 15 and 25 vol. % B₄C reinforcement particles in Al-%4Cu matrix. Utilized powders were pure aluminum powder (Alfa Aesar, purity >99.5%, particle size <10 microns), Copper (Merck, purity >99.7%, dendritic, -63 micron), B₄C (Alfa Aesar, purity >99, <10 microns).

Al, Cu and B₄C powders were weighed in proper amounts, separately for the 4 layers of the FGM. The amounts of the constituents of each layer are presented in Table 1. The theoretical thickness of each layer was calculated to be 1.6 mm and the total thickness of the FGM was planned as 6.4 mm. The width of the sample was 12 mm and length was 33 mm. These dimensions are suitable for 3-point bending sample according to ASTM B528 standard entitled: Standard Test Method for Transverse Rupture Strength of Metal Powder Specimens. The unreinforced sample contained Al-%4Cu of 7.768 g. The sample having 25 % B₄C in its whole body was composed of 5.826 g Al-%4Cu and 1.762 g B₄C.

Table 1: Amounts of the constituents of each layer in FGM.

Layer No	B ₄ C Vol. %	Wt. Al-%4Cu (g)	Wt. B ₄ C (g)
1	0	1,94	0
2	5	1.8449	0,0881
3	15	1.6507	0,2643
4	25	1.4565	0.4405

Al, Cu and B₄C powders were mixed separately for each layer and the mixtures were placed on top of each other in a tool-steel die in layered fashion. The mixtures were lightly pressed after each layer. The parts of the steel die were covered with stearic acid, in order to reduce die friction and to prevent the sticking of the pressed article to the die. After weighing and measuring the dimensions of the samples, they were placed in the hot zone of a tube furnace. Samples were sintered at 610 °C for 30 min in high purity nitrogen atmosphere. After sintering, they were subjected to microstructural examinations by optical microscope (Nicon Eclipse, LV150),

microhardness measurement in HV0.1 scale and 3-point bending tests (Shimadzu AG-IC 50 kN).

3. Results and Discussion

After sintering FGM sample and unreinforced Al-4%Cu sample presented a slight distortion in the form of bending in one direction. Therefore a slight curvature formed on one side of the samples. This effect was more pronounced in the FGM sample as compared to unreinforced Al-4%Cu sample (Fig.1). Two reasons can be proposed for this behavior. One is the uneven green density of the article, origination from uni-axial pressing in the die. The second is the uneven green density of the article, originating from the different amount of B₄C particles in the layers of the FGM. On the contrary to other samples, this effect was not observed in the 25 % B₄C reinforced Al-4%Cu sample, and that sample was flat.

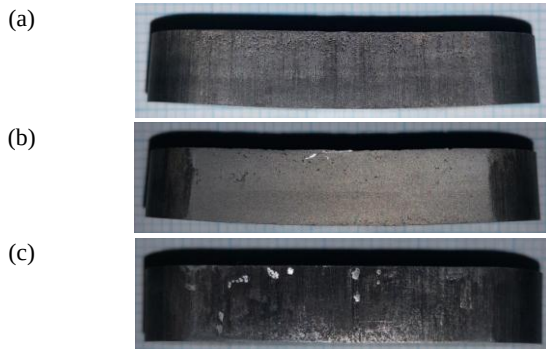


Fig. 1 Macro images of the samples after sintering. (a) unreinforced Al-4%Cu, (b) FGM, (c) 25 % B₄C reinforced Al-4%Cu.

Micrographs of the layers in the FGM structure containing 5, 15 and 25 % B₄C are presented in Fig.2. It can be seen that B₄C particles are in general homogenously distributed in the microstructure. The amount of B₄C in the microstructure increases in accordance with the reinforcement content of the layers.

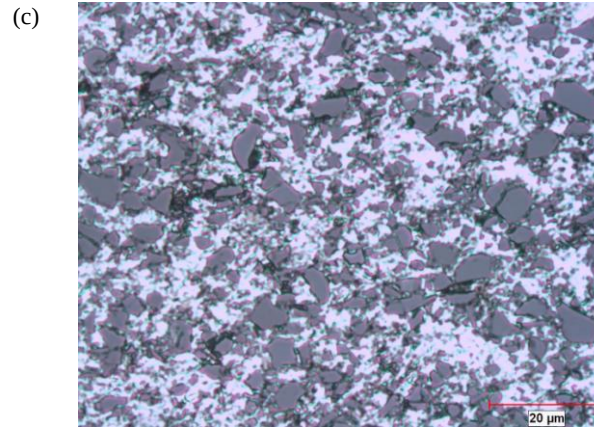
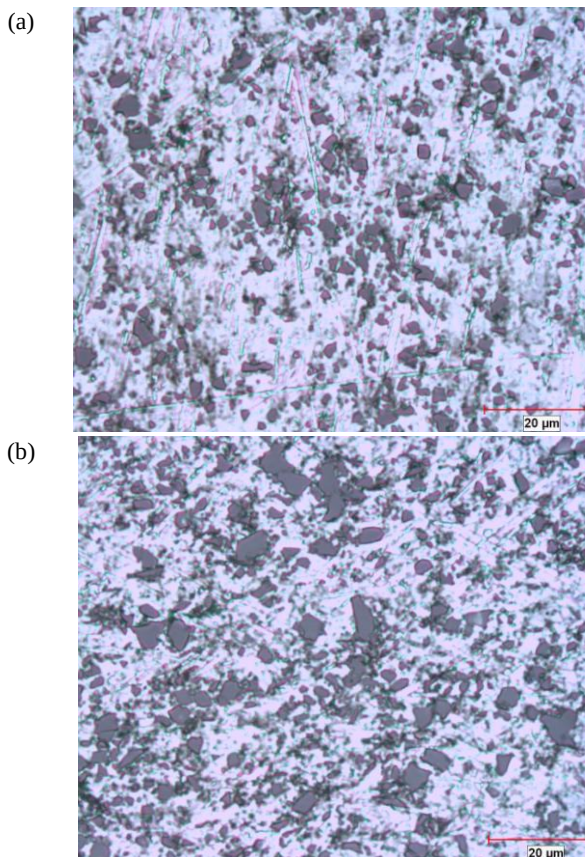


Fig. 2 Optical microscope images of the layers after sintering, containing (a) 5% B₄C, (b) 15% B₄C FGM, (c) 25% B₄C.

It can also be seen that porosity (black regions in the micrographs) increases in the structure with the increase in the amount of B₄C particles. The pores appear to form among the groups of B₄C particles (Fig. 2(c)). Higher sintering temperature or pressure assisted sintering may be effective in reducing these pores.

Microhardness values of the layers of the FGM sample is presented in Fig.3 as a function of B₄C content. Hardness of the unreinforced layer was 60.0 ± 4.14 HV0.1. Hardness increased steadily with the increase in the amount of B₄C reinforcement particles in the layers. Hardness of the layer containing 25 % B₄C was 115.7 ± 1.87 HV0.1.

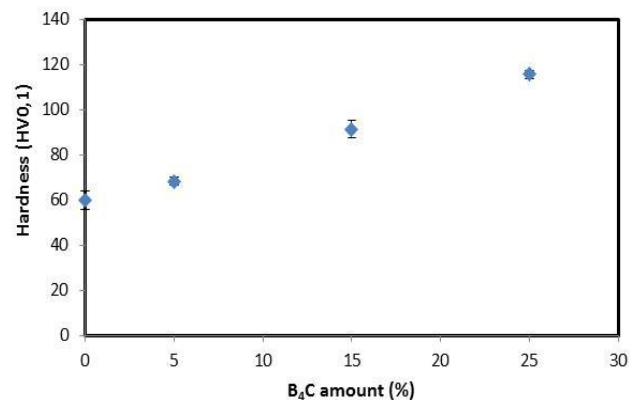


Fig. 3 Vickers microhardness values of the layers in FGM as a function of B₄C content

Stress-strain curves of the samples obtained by three point bending tests are presented in Fig.4. The unreinforced sample exhibited a bending strength of 375 MPa, with about 25 % strain. Therefore the unreinforced sample presented a quite ductile behavior, with high amount of plastic deformation. The macro image of the unreinforced sample given in Fig. 5(a) supports this outcome.

The composite sample containing 25 % B₄C in its whole body had a bending strength of 150 MPa, with about 3.6 % strain. This results indicates that the sample reinforced with 25 % B₄C fails in a brittle manner. Indeed, the macro structure of this sample presented no indication of plastic deformation (Fig. 5(c)). The reason for the brittle behavior may be due to the discontinuity of the matrix phase due to the presence of B₄C particles and the pores.

The FGM sample, on the other hand, presented a behavior that is in between the unreinforced sample and the sample reinforced with 35 % B₄C, in terms of bending strength and strain. Bending strength of the FGM sample was 150 MPa and strain was 10.7%.

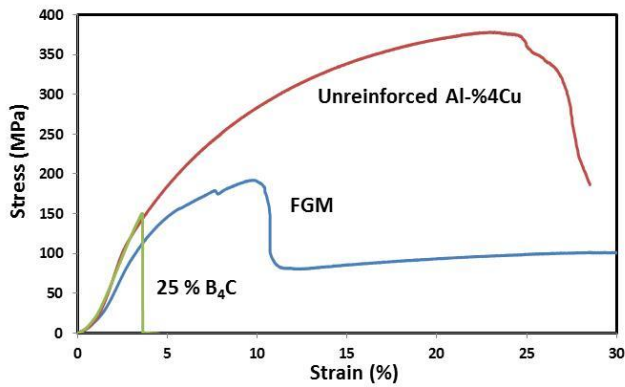


Fig. 4 Stress-strain plots of the samples obtained by three point bending tests.

The fracture of the FGM sample exhibited steps, in which the stress on the sample decreased during the bending test. The first step in the stress-strain plot of the FGM sample took place due to interlayer separation during the bending test. The interface between the layer containing 5 % B_4C and 15% B_4C was seen to delaminate horizontally during the test at this point. This delamination indicates the poor bonding of the matrix alloy between these layers during sintering. The poor bonding may have resulted due to pressing after laying each layer in the die.

The second and larger drop in the stress value that took place at about 10.7 % strain was due to vertical cracking of the layers. The cracking occurred in the top 2 layers of the FGM, which contained 15 and 25 % B_4C . These layers are expected to be less ductile than the other layers of the FGM. The vertical cracks in these layers can be seen in Fig.5(b). The bottom two layers of the FGM did not exhibit vertical cracking, indicating their ductile behavior. They presented high amount of plastic deformation.

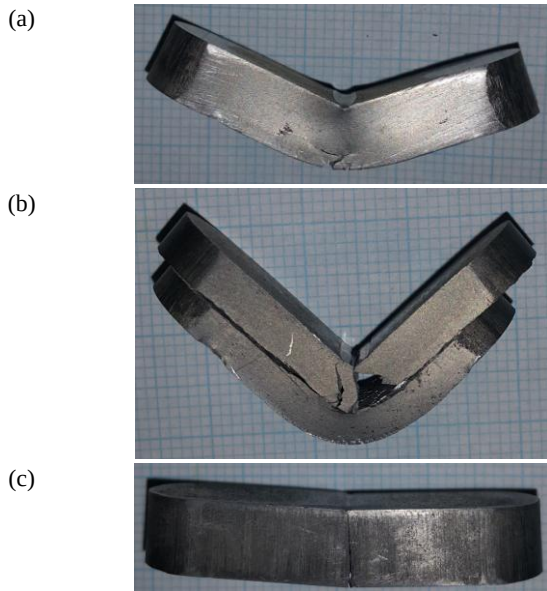


Fig. 5 Macro images of the samples after 3 point bending test. (a) unreinforced Al-4Cu, (b) FGM containing 0, 5, 15, 25 % B_4C reinforced layers, (c) 25 % B_4C reinforced Al-4Cu.

4. Conclusion

Functionally graded materials (FGM) containing B_4C particles at amounts of 0, 5, 15 and 25 volume % within 4 layers in an aluminum matrix were produced and characterized. The plain sample had a 3-point bending strength of 380 MPa, whereas that of the 25 % B_4C composite was 140 MPa. The FGM sample presented a bending strength of 190 MPa. The failure of the FGM sample was composed of steps which were suggested to originate due to delamination and fracture of the layers containing 15 and 25 % B_4C . It can be proposed that in order to obtain better mechanical properties from the FGM, a better bonding between the interlayers is crucial.

Acknowledgements

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FEATURES OF WEAR OF RAILWAY WHEELS TREAD

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Abstract. Causes of wear particles formation on railway wheels tread were investigated. Structural factors connecting with plastic deformation, formation of "white layer", and also with non-metallic inclusions and corrosive products of wheel steel, defining wear of railway wheels tread during operation were fixed. Repeating heat-mechanical action on railway wheel tread by interaction between wheel and rail promotes incandescence of stresses and defects (microcracks, separations) that promote wear particles formation having different shape, source and mechanism of nucleation. Results of analysis of microcracks, spalls and wear particles and also of mechanisms of their formation was shown that wear of railway wheel tread is very composite phenomenon. It passes by few mechanisms (fatigue, adsorbational, corrosive, under friction) and is multifactors process.

KEYWORDS: WEAR PARTICLES, RAILWAY WHEELS, TREAD.

1. INTRODUCTION.

Complex approach for wear mechanism of railway wheels includes not only investigation of structural changes happening in surface layers of wheel rims [1-6], but also analysis of wear particles and establishment of mechanism of their formation. The variety of working conditions of friction pairs suggests that the general approach may be the idea of the fatigue nature of the destruction of the surface layers [7,8]. Interest for investigation of wear mechanism connects not only with necessity of cutting down of wear losses but also with development of effective methods of prediction of wheels service life, and with ensuring of their operation especially in extremal conditions. Wear mechanism of railway wheels tread presents assemblage of mechanical, thermo-physical and chemical effects. It connects with wear particles and microcracks formation in areas of intensive plastic deformation and "white layer", near non-metallic inclusions and corrosive products of wheel steel [1-6,9,10]. Influence of some structural changes on the wear of tread was discussed [1-6] but analysis of these processes on mechanisms of wear particles formation on railway wheels tread during operation was not conducted.

The goal of this work was investigation of mechanisms of wear particles formation on railway wheels tread during operation.

2. MATERIALS AND METHODS OF INVESTIGATION

Mechanism of wear of railway wheels made of steel R7 and operated about 5 years under passenger rolling stock was researched. Wheels were taken off operation by limit wear of rims. Microstructure of wheel steel and defects were investigated by a few methods: metallographical, micro X-ray spectral, X-ray diffraction analysis, electron microscopic.

3. INVESTIGATION RESULTS AND DISCUSSION

Analysis shown that along the whole railway wheels tread microcracks and separations resulting in formation and spalling of wear particles and brittle fracture of cove zone were discovered. Formation of wear particles has different causes. Shape of wear particles depends on conditions of their formation.

During the initial stages of the railway wheel operation, this effect promotes burnishing of roughnesses on the wheel and rail surfaces allowing the wheel profile to change, which accelerates the so-called useful wear necessary to speed up the process of running in the wheel-rail system. Further it is necessary improvement the limit condition of deformational strengthening of steel for the formation of surface defects (wear particles). This stage of deformation is quickened under action of surface-reactive medium [11]. In the time of formation and spalling of wear particles the new "fresh" surfaces of cracks are appeared

One of main cause of wear particles formation is plastic shears proceeding near tread with big degree of deformation which has heterogeneous character [1-6]. On the boundaries of zones with different degree of deformation and also in areas of intensive and turbulent deformation the microcracks (fig. 1, a) and wear particles (fig. 1, b) are formed. In cove zone the group of wear particles was formed that evidences about considerable localization of plastic deformation and results in fracture of crest.

Wear particles formed on account of development of intensive plastic deformation near tread have the shape of scales or plates with different thickness. They are typical for normal conditions of wear [7]. According to wear theory by "spalling" [1-6] maximum dislocation density under wear origins is not near surface but on the some depth. Just microcracks growing to critical size in the results of plastic flow of steel are formed (fig. 1, c, d). Plastic flow of steel are localized between microcracks and wheel tread and particles having shape of scales are formed and spalled. Formation of wear particles happens in the result of ductile spalled of metal in the time of coalescence of these microcracks and are accompanied of plastic flow of steel near wheel tread.

Data by definition of dislocation density on and near wheel tread citing in [1-6] evidence about development of intensive plastic deformation during operation of railway wheels. Dislocation density was $10^{10} \dots 10^{11} \text{ cm}^{-2}$ on wheel tread, but on the depth of 100-200 μm from wheel tread it was higher about in 2...3 time as compared with wheel tread. Such difference of dislocation density connects with going out of moving dislocations on free surface during plastic deformation. In addition to it is known the fact of "braiding" influence of surface (in our case it is wheel tread) on moving dislocations. Wear stresses for wear particles with definite thickness near wheel tread were defined [1-6].

Considering the features of plastic deformation development in wheel steel near wheel tread it is essentially to take into account interaction of this surface with ambient air bring to formation of corrosive damages. It is known the elementary stage of corrosion includes adsorption of atoms of elements from damp ambient air that can to evoke effect of adsorption to facilitate plastic deformation near wheel tread (Rehinder effect) [11].

and these surfaces adsorb atoms of elements from damp ambient air active. Adsorption penetration of surface-reactive elements into cracks happens with high rate [11] that result in fall of surface energy of cracks (and work of their formation) and also makes easier their development in process of plastic deformation of steel. Thus, a wet environment, which also contains various lubricants, impurities, etc., has a negative effect on the fatigue strength of the wheel surface due to its adsorption and corrosive effects.

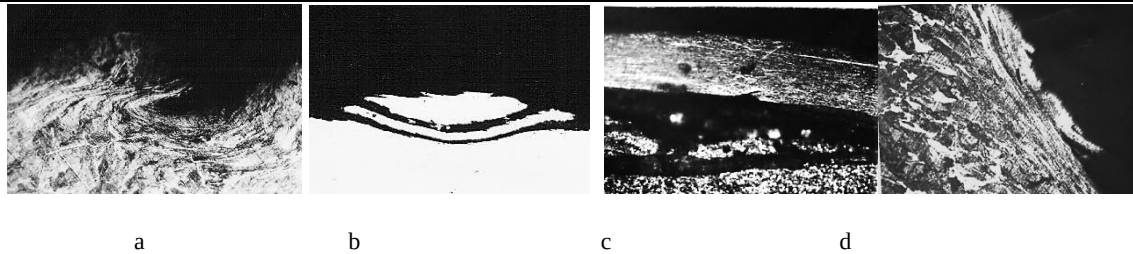


Fig. 1. Wear particles near tread in zone of intensive plastic deformation; a – $\times 100$, b – d – $\times 200$

According to the data of [8], wear particles, which are flakes or plates of different thickness, are formed with a uniform distribution of dislocations over the thickness of these flake particles. After the formation of these flaky particles, some of them fall between the two sliding surfaces of the wheel and the rail, as a result they can be broken in shape or destroyed, or remain the same size and "flat" shape.

Wear of the wheel surface, accompanied by the development of intense plastic deformation, occurs in layers and each layer consists of a large number of scales - wear particles. Their number N in each layer is proportional to the number of microcracks formed during plastic deformation. The rate of fusion of microcracks and the critical degree of deformation required for the formation of free wear particles depend on the depth of the plastic deformation zone with the maximum density of dislocations. The overall wear of the tread during the development of plastic deformation, the size and level of roughness of wear particles, the wear rate of the tread have been determined. Obviously, the wear rate decreases when the intensity of plastic deformation in the surface layer of the wheel rim decreases.

The second source of the formation of wear particles on the tread of wheel is the so-called "white layer", which has an increased brittleness [1-6]. The localization of deformation of the surface layer of the wheel rim is detected near the "white layer"

areas, which contributes to stress concentration and chipping of the "white layer". Wear particles have the shape of splinters with sharp edges of irregular shape (Fig. 2 b). They usually occur at very high pressures and their appearance can be associated with the formation of small fatigue cracks in the surface layers of the rims [7]. It should be noted that under the brittle "white layer" steel is plastically deformed and repulsive forces appear at the border of these structural components acting on moving dislocations [8]. This can lead to the appearance of microcracks both along the border of the "white layer" - deformed steel structure, and at some distance from it, similar to those shown in fig. 1c and parallel to the rolling surface of the wheel (Fig. 2 b). For the transformation of such microcracks into wear particles, the reasoning given above is valid.

The third reason for the formation of wear particles are non-metallic inclusions that are of metallurgical origin and are stress and strain concentrators in the wheel steel [12,13]. The formation of cracks and wear particles also contributes to the oxidation and corrosive destruction of the tread, and these processes lead to the formation of coarse oxides of coarse inclusions directly on the tread. The presence of inclusions and corrosion products significantly increases the rate of formation of microcracks and their combination, which increases the intensity of wear (both fatigue and friction) [12,13].

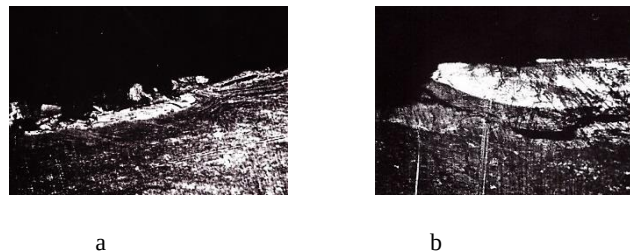


Fig. 2. Wear particles in areas of the "white layer"; $\times 1000$

Analysis of the microstructure of the wheel steel near treads of the wheels showed that non-metallic inclusions and corrosion products of the wheel steel contribute to the non-uniform development of deformation, the appearance of turbulent

The behavior of non-metallic inclusions located near the tread under the influence of acting stresses depends on their type [12]. They are plastic (sulphides) or not subject to plastic deformation (oxides, silicates, titanium carbonitrides). Non-metallic inclusion, located near the wheel tread, is in a complex stress state determined by a system of contact, dynamic and cyclic stresses. The temperature gradient arising during the operation of the wheel near the tread leads to a non-uniform distribution of deformations in the steel matrix and the forces acting on the inclusion.

Under conditions of high pressures and cyclically varying temperatures, the interaction of the contact surfaces of the inclusion and the steel matrix occurs by establishing mechanical contact and the development of diffusion processes. Mechanical contact is established as a result of smoothing the irregularities of the surfaces of the inclusion and the matrix of the wheel steel by developing the contact friction of their surfaces relative to each other, preventing their relative movement. Such

flow zones (Fig. 3 a) and also contribute to the formation of zones with increased degree of deformation.

friction is a kinematic dry sliding friction [12,14]. The conditions of friction on the interphase boundaries of non-metallic inclusion-steel matrix have been analyzed [9]. Contact friction enhances the non-uniformity of deformation of the wheel steel matrix near the inclusions, which can have an impact not only on the level of stresses acting on the inclusion, but also on the stress state scheme [12,15]. In the process of contact interaction of inclusions and the steel matrix, the inclusions can rotate (Fig. 3a), which causes momentary stresses and contributes to local plastic rotations in the steel matrix as a result of its vortex flow.

In the process of joint deformation of the inclusion-matrix system near the tread of the wheel, a characteristic fibrous grain structure of the wheel steel is formed (Fig. 3a). The fibers of the matrix round the inclusion, gradually "bumping" on it (Fig. 3 b - d), and stratification along the interfacial interfaces of the inclusion-matrix is possible. In this case, at the boundaries of the inclusion-matrix, compressive and shear stresses are concentrated, which can destroy the inclusion if they exceed the

tensile strength of the inclusions under compression. Similar processes occur near corrosion products (Fig. 3 e, f).

Under accelerated braking under conditions of a sharp rise in temperature, the possible role of slipping along grain boundaries in austenite and on the interfacial boundaries in the development of deformation near the tread of the wheel should

be considered [1-6]. It should be noted that non-metallic inclusions are often the centers of local decarburization of steel (see Fig. 3 c), which causes structural heterogeneity and entails a heterogeneous development of plastic shears, as well as the formation of microcracks and wear particles.

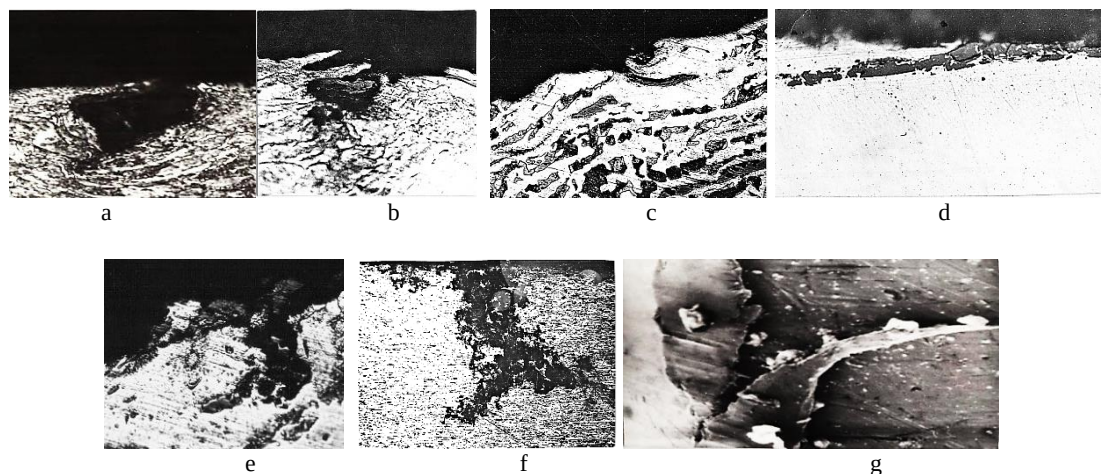


Fig. 3. Localization of deformation (a) and formation of wear particles near non-metallic inclusions and corrosive products of wheel steel (b – g) on railway wheel tread: a, b, g –x400, c – f – x200

It is necessary to consider another aspect of the influence of low-melting non-metallic inclusions on the formation of wear particles near tread of railway wheels under conditions of emergency braking and local heating of the tread to temperatures corresponding to the austenitic region, when melting and even melting of low-melting iron-manganese sulfides and sulfide eutectics can occur [12-16]. Then the manifestation of local sulphide red brittleness is possible [16], when the ductility and strength of wheel steel are sharply reduced. If the tread of the wheel heats up to high temperatures, the sulfide inclusions melt (Fig. 4 a), there is a sharp localization of the steel deformation and a lot of cracks occur, that is, the steel is destroyed when relatively low degrees of deformation are reached. Liquid interlayers are easily drawn out parallel to the tread of the wheel (Fig. 4 b), cracks

propagate between them, contributing to the formation of wear particles.

Near non-metallic inclusions and corrosion products of wheel steel, wear particles have the form of loops, spirals, similar to cutting chips during cutting (Fig. 3 g). They take this form due to residual stresses associated with the inhomogeneous distribution of dislocations over the thickness of wear particles formed near the inclusions [8]. According to [9,10], such wear particles precede damage and are found mainly on the tread before local destruction. In the case of local sulphide red brittleness of steel in areas of the tread, where sulphide inclusions melted, there are many wear particles of both spiral and compact irregular shapes (Fig. 4c), which is caused by the presence of many microcracks in these zones, as well as crushing of particles wear due to strong localization of deformation.



Fig. 4. Formation of wear particles in zones of sulphide red brittleness on railway wheels tread; x600

Considering the effect of corrosion products on the formation of wear particles, one more aspect of the influence on the development of fatigue failure on the tread of the external environment should be taken into account. It was noted above that the initial stage of corrosion involves the adsorption of atoms of elements from the environment, which causes an effect of adsorption lowering the strength of the product (the Rehbinder effect) [11]. Plastic shears arising in the surface layer of the rim (near tread), thermal cycling during braking and also interaction with the surrounding atmosphere create conditions for the intensive development of diffusion processes that contribute to more intensive adsorption of elements from the environment. Adsorption-fatigue phenomena occur on the tread surface of the railway wheel, leading to the nucleation of fatigue cracks and wear particles and accompanying their growth and detachment [7]. The presence of

interphase boundaries non-metallic inclusion-steel matrix with their defect structure and interphase stresses [17], as well as the formation of microcracks in them undoubtedly contributes to the localization of the effect of the adsorption decrease in the tread strength of the railway wheel near non-metallic inclusions, which is energetically characterized by a decrease in the formation of new solid surfaces in the process of deformation and destruction under the influence of the formation of an adsorption layer on them [11]. Apparently, for the interphase boundaries of the inclusion-matrix, the force interpretation of the effect of the adsorption decrease in strength is particularly relevant, due to the occurrence of a wedging effort within these boundaries, contributing to the penetration of the adsorption layer into the depth of the tread [10], which in turn contributes to the detachment of inclusions from steel matrix and the formation of wear particles.

4. CONCLUSIONS.

Repeating heat-mechanical action on railway wheel tread by interaction between wheel and rail promotes incandescence of stresses and defects (microcracks, separations) that promote wear particles formation having different shape, source and mechanism of nucleation:

- More wide-spread wear particles are the scales or plates with different thickness. Formation of such wear scales happens in the result of ductile spalling of metal. They are typical for normal conditions of wear and their appearance connects with plastic deformation near wheel tread.
- By brittle fracture of areas of "white layer" wear particles are formed with shape of fractions with sharp edges. Their appearance one can to connect with formation of fatigue microcracks in surface layers of wheel rims. Spreading of fatigue microcracks to surface is the beginning of wear particles formation.

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- Wear particles near non-metallic inclusions and corrosive products of wheel steel have shape of loops or spirals. They are formed by localization of deformation near inclusions and galling of metal matrix on the inclusions and also in the results of separation of interphase boundaries non-metallic inclusion-steel matrix. Such wear particles are discovered on wheel tread before local fracture.

- In the cause of local sulphide red brittleness a great number of wear particles with spirals and compact irregular shape were observed. This connects with presence of a great number of microcracks in these areas and also with grinding of wear particles by tough localization of deformation.

Results of analysis of microcracks, spalles and wear particles and also of mechanisms of their formation was shown that wear of railway wheel tread is very composite phenomenon. It passes by few mechanisms (fatigue, adsorbition, corrosive, under friction) and is multifactors process.

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THE PHENOMENON OF REVERSION IN AGING MAGNESIUM ALLOYS WITH THE RARE-EARTH METALS

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Abstract: The reversion in magnesium binary alloys with rare-earth metals (Nd, Sm, Y, Gd, Tb, Dy, Ho) at a temperature of 300°C has been studied. The phenomenon of the reverse dissolution of rare-earth metals in solid magnesium has been established to begin in all alloys under study already after short-term annealing at 300°C for 15 min. As the annealing time at 300°C further increases, the reverse dissolution of rare-earth metals in solid magnesium first continues and then the magnesium solid solution becomes again depleted of rare-earth metals because of their precipitation. The degree of reversion has been found to generally increase with an increase in the atomic number of the yttrium-group rare-earth metal in accordance with its position in the lanthanum row: Gd, Tb, Dy, and Ho. The degree of reversion in the alloys with cerium-group metals (Nd, Sm) with atomic numbers below those of Gd, Tb, Dy, and Ho is substantially smaller than that is in the alloys with yttrium-group metals.

Keywords: MAGNESIUM ALLOYS, RARE-EARTH METALS, REVERSION, SOLID SOLUTION DECOMPOSITION, STRUCTURE.

1. Introduction

Magnesium alloys are used in modern industry as light structural materials. The addition of rare-earth metals to magnesium can substantially improve their strength characteristics at both ambient and elevated (200-300°C) temperatures [1 - 4]. However, upon short-term holdings at not-too-high temperatures, the magnesium alloys age-hardened to high strength exhibit the phenomenon of reversion, which can lead to weakening because the REM-containing hardening particles precipitated upon aging undergo a reverse dissolution in the magnesium solid solution [5 - 7]. The reversion process should lead to a decrease in strength properties, especially at elevated temperatures. The paper presents the results of the study of reversion at a temperature of 300°C in the magnesium alloys containing rare-earth metals of cerium (Nd, Sm) and yttrium groups (Y, Ho, Dy, Tb) after age hardening at 200°C for the maximum strength.

2. Experimental

The alloys for the study were prepared by melting in an electric resistance furnace in iron crucibles under the standard VI2 flux containing 38-46% MgCl₂, 32-40% KCl, 5-8% BaCl₂, 3-5% CaF₂, which was used for the protection of the molten magnesium from ignition. Magnesium Mg95 (>99.95% Mg) and rare-earth metals such as ItM-1 yttrium, NM-1 neodymium, SmM-1 samarium, GdM-1 gadolinium, TbM-1 terbium, DiM-1 dysprosium, and GoM-1 holmium at least 99.83% pure (hereinafter, the compositions are given in wt.%) were used as the starting materials. The rare-earth metals were added into the Mg melt upon melting as master alloys. The rare-earth metals for the study were chosen because, in binary magnesium alloys, they provide a substantial strengthening effect caused by the decomposition of the supersaturated magnesium solid solution upon aging [3]. The alloy compositions were chosen with allowance for the binary phase diagrams in such a way that the content of each rare-earth metal was somewhat below its solubility in solid magnesium at the homogenization temperature. Table 1 shows the alloy chemical compositions analyzed by inductively coupled plasma atomic emission spectroscopy with an Ultima 2C Jobin-Yvon instrument.

The alloys were cast into a stainless steel mold heated to ~300°C to obtain cylindrical ingots of 15 mm in diameter and 90 mm long. The ingots were cut into blanks, which were subjected to homogenization annealing for 6 hours at temperatures given in Table 1. The blanks after homogenization annealing were quenched in room-temperature water in order to obtain a supersaturated magnesium solid solution.

Table 1: Alloys compositions, homogenization temperatures, and aging time at 200°C for achievement of the maximum hardness

Alloy composition	Homogenization temperature, °C	Aging time at 200°C for the achievement of maximum hardness
Mg-8.3% Y	540	128
Mg-2.2% Nd	530	4
Mg-3.5% Sm	520	16
Mg-15.5% Gd	520	32
Mg-17.7% Tb	540	32
Mg-19.5% Dy	540	128
Mg-21.4% Ho	540	128

Samples for the hardness and electrical resistivity measurements were made from the quenched blanks of the alloys.

The hardness was tested by the Brinell method with a TSh-2M tester using a ball of 5 mm in diameter at a load of 2500 N. Electrical resistivity of the samples of 6 mm in gage diameter and 23.7 mm in gage length was measured with a unit based on the BSZ-010-2 microohmmeter. The error of the electrical resistivity measurement was about 0.7%. The microstructure of the alloys was examined with an M 24 Reichert metallographic microscope. The polished samples were etched with 0.5% nitric acid solution in ethanol or 30% orthophosphoric acid solution in ethanol.

3. Results and discussion

At the first stage of the study, the alloy samples after homogenization and quenching were subjected to isothermal aging at 200°C for up to 128 hours with the view to follow the process of age hardening upon decomposition of the supersaturated magnesium solid solution by measuring hardness and to establish the aging time, at which the maximum hardness is reached. The established aging times required to achieve the maximum hardening at 200°C in the alloys are given in Table 1. Then the alloys were subjected to isothermal annealing at 300°C for 0.25 - 128 hours to detect reversion. The results of the hardness and resistivity measurements for the alloys aged for maximum hardening at 200°C and then annealed at 300°C for the study of the reversion are shown in Figs. 1 and 2.

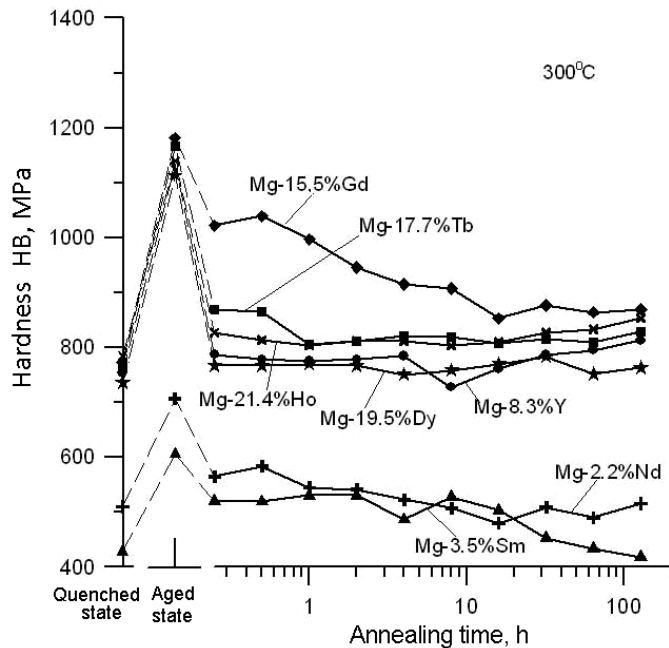


Fig. 1. Hardness of the REM-containing magnesium alloys quenched and aged at 200°C for the maximum hardening as a function of time of subsequent isothermal annealing at 300°C.

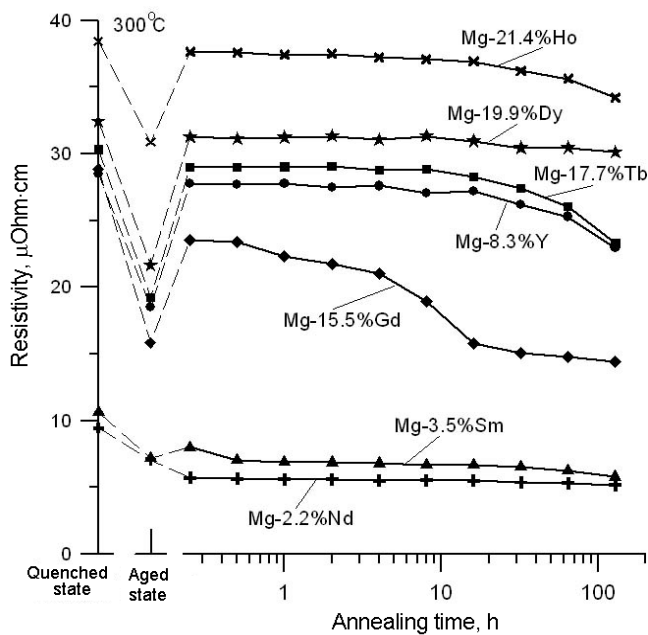


Fig. 2. Electrical resistivity of the REM-containing magnesium alloys quenched and aged at 200°C for the maximum hardening as a function of time of subsequent isothermal annealing at 300°C.

According to the data presented in Fig. 1, the hardness of the aged magnesium alloys with rare-earth metals is abruptly reduced even after the shortest (15 min) annealing at 300°C, especially in the alloys with yttrium group rare-earth metals (Y, Gd, Tb, Dy, Ho). This suggests the possibility of the reversion phenomenon, i.e., the reverse dissolution of rare-earth metals in solid magnesium. Such reversion effect presumed according to change in hardness becomes proven by the observed increase in resistivity after annealing by the same regime (Fig. 2). The resistivity data show that, with a further increase in the annealing time at 300°C, first the reverse dissolution of rare-earth metals in solid magnesium remains unchanged, and then the magnesium solid solution becomes again depleted because of the precipitation of rare-earth metals. The degree of reversion is substantially smaller in the magnesium alloys with cerium-group

rare-earth metals, which have been studied for comparison, and can be even absent in the magnesium alloy with neodymium.

The degree of reversion was evaluated by the formula: $S = (\rho_{\text{ann}} - \rho_{\text{ag}}) / (\rho_{\text{q}} - \rho_{\text{ag}})$, where S is the degree of reversion, and ρ_{ann} , ρ_{ag} , and ρ_{q} are the resistivities of the alloy in the states after annealing at 300°C for the maximum reversion, after aging to the highest hardening at 200°C, and after quenching, respectively. The results obtained are given in Table 2. Note that the degree of reversion in the magnesium alloys with yttrium group rare-earth metals of the lanthanum row (Gd, Tb, Dy, Ho) increases with increasing their atomic number. The degree of reversion of magnesium alloy with yttrium, which does not belong to the lanthanum row, is close to that of the magnesium alloys with the lanthanum row metals such as dysprosium and holmium. The reversion after aging in the alloys with cerium group metals is substantially smaller than in the alloys with yttrium group metals and can be even absent, as in the alloy with neodymium. An increase in the degree of reversion with increasing atomic number of yttrium group rare-earth metals of the lanthanum row (Gd, Tb, Dy, Ho) was also observed in the same alloys upon annealing at a temperature of 250°C [7].

Table 2: Degree of reversion in aged magnesium alloys with rare-earth metals after annealing at 300°C.

Atomic number of REM	Alloy	Degree of reversion, %
60	Mg - 2.2% Nd	0
62	Mg - 3.5% Sm	24.1
64	Mg - 15.5% Gd	58.8
65	Mg - 17.7% Tb	88.8
66	Mg - 19.5% Dy	89.9
67	Mg - 21.4% Ho	89.5
39	Mg - 8.3% Y	92.3

The microstructure examination of the alloys by optical microscopy did not reveal any signs of the decomposition of the supersaturated magnesium solid solution after aging to the maximum hardness and after reversion after short-term annealing at 300°C. This can be explained by very fine precipitates from the magnesium solid solution and by the retention of the coherence between the crystal lattices of the precipitates and the magnesium solid solution. However, after long-term annealing following the reversion at 300°C, optical microscopy revealed the decomposition of the magnesium solid solution in the structure of the alloys in the form of the particles precipitated at three planes of the crystal lattice of the magnesium solid solution and at grain boundaries (Fig. 3). With allowance for the results reported in [3, 8, 9], we can assume that the increase in hardness up to the stage of the maximum strengthening is due to the formation of a metastable β' phase, which is typical for the decomposition of the magnesium solid solution in the magnesium alloys with yttrium group rare-earth metals. This phase has a base-centered orthorhombic crystal lattice.

4. Conclusions

1. It is established that the binary magnesium alloys with yttrium group rare-earth metals (yttrium, gadolinium, terbium, dysprosium, and holmium) after age hardening can undergo a substantial reversion with the reverse dissolution of the particles precipitated upon the decomposition of the supersaturated solid solution.

2. The degree of reversion sequentially increases with increasing atomic number of the rare-earth metals belonging to

yttrium group of the lanthanum row from Gd to Tb, Dy, and Ho. The degree of reversion of the magnesium alloy with yttrium, which does not belong to the lanthanum group, is close to those of the alloy with holmium and dysprosium. The reversion in the magnesium alloys with cerium group rare-earth metals is substantially smaller than that in the magnesium alloys with yttrium group metals and can be even virtually absent.

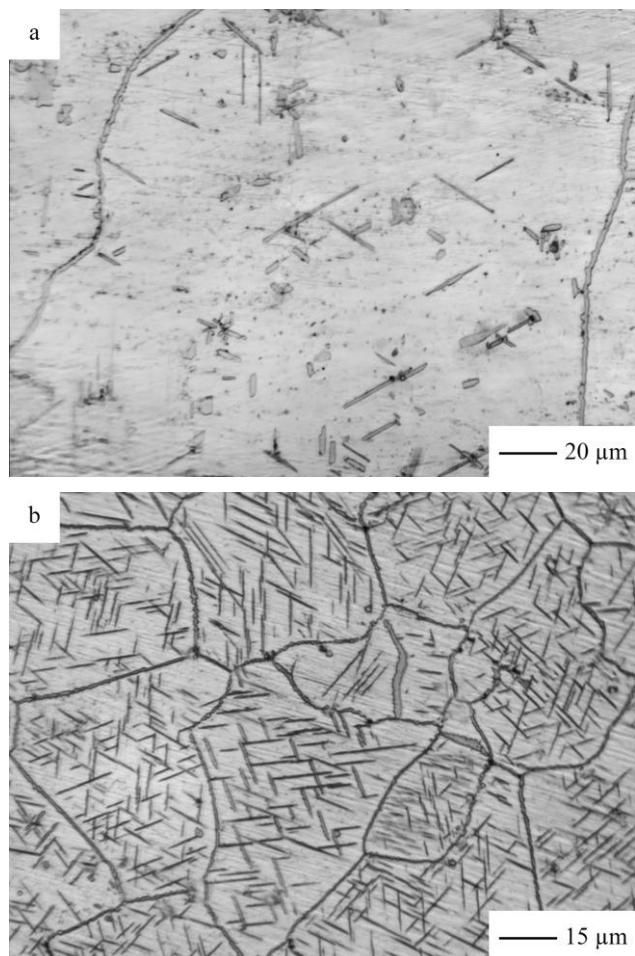


Fig.3 Typical microstructures of the alloys: Mg - 8.3% Y (a), and Mg - 17.7% Tb (b) after quenching + aging at 200°C + annealing at 300°C for 128 h.

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