

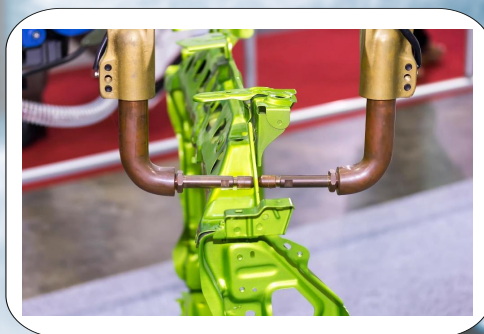
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Determination of resistance to motion during operation of belt conveyor

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Abstract: Belt conveyors play a significant role in the transport of bulk materials due to a number of advantages such as: high capacity, economy, safety and reliability. The belt conveyor for bulk materials was observed in this paper. In order to drive the belt conveyor, the power of the driving electric motor must overcome all the resistances that occur during the transport of materials. The paper presents one of the possible approaches to the method of calculation and selection of belt conveyor parameters. The conveyor travel path was adopted, all resistances to the motion of the belt and materials were defined and the calculation of the total resistance to motion on characteristic transport sections was performed. The influence of conveyor loading and discharge devices, drive mechanism, way of moving the belt over the rollers were taken into account. The general calculation algorithm is presented and a graphical representation of the conveyor assemblies is given for the defined transport route.

Keywords: BELT CONVEYOR, BULK MATERIALS, RESISTANCE, 3D MODEL

1. Introduction

Belt conveyors are most commonly used conveyors for material handling. This paper considers a belt conveyor for handling bulk materials which are stored in heaps. The belt conveyor handles materials such as: minerals (ores, coals), earthly materials (gravel, sand, clay), processed materials (cement, salt, chemicals), agricultural products (grain, sugar, flour) and other similar powdery, granular or lumpy materials. Regarding the handling of bulk materials, their major features are: lump-size, bulk weight, specific weight, moisture content, mobility of its particles, angles of repose, abrasiveness, temperature, proneness to explosion, stickiness, corrosivity and hygroscopic properties [1].

Although the belt conveyors have been used for many years, there are still some problems in exploitation to be solved [2]. The companies that use the belt conveyors demand that they have high performance and high reliability. This may be achieved in the design phase, using mathematical models and simulations, which can have significant effect on reliability and exploitation of the belt conveyors. The mathematical model that provides the analysis of the belt conveyor dynamics was presented in [2].

Design of the belt conveyors meets many challenges. Mechanical components, such as idlers, drives, pulleys and many accessories are constantly developed to improve the performance and durability of the belt conveyor. Compared to other means of transport, belt conveyors demand low labour and energy consumption.

In [3], the analysis of force ratios of conveyor belt was conducted based on the formed geometrical model with application of FE analyses. Calculations, selection and modelling of the main elements of the belt conveyors were performed in [4, 5].

The method of measuring the resistances to motion of a single three-roller idler set with the use of a specially designed measuring stand was presented in [6]. Measurements performed in mine conditions provided the records of the real forces that exert load on the tested measuring set determination of the motion resistances of the set. This has enabled the analysis of the effect of belt conveyor design parameters on its resistances to motion.

2. Calculation

In order to commence the design stage of the belt conveyors, it is necessary to estimate the characteristics of the material which will be transported by that conveyor. In this study, coal was the material to be transported by the belt conveyor. The following initial data were taken into account: transport capacity, route scheme, characteristics of the transported material, mode of operation, and operating conditions.

The belt conveyors with rubber belt are the basic means for continuous transport of the bulk materials. The belt conveyors can practically be designed for any desired travel path. Their use is

limited by the strength of belt, angle of incline or decline, and available space.

The successful design of the belt conveyor depends on both the characteristics of the material being transported and the behaviour of the materials on a moving belt. The optimal acceptable speed for transporting a specific material was chosen. In addition, the carrying and return idlers designs were adopted. The calculations of the belt, belt tension and motor drive power were conducted. All influential factors in the calculation are listed in the appropriate formulas. The methodology of calculation of the supporting structure is stated, as well as of the drive and of the return pulley.

During the design process, it is very important to properly determine the cross-sectional area of the material on the belt and, consequently, the calculation capacity of the belt conveyor. Also, it is important to optimally define the belt width and operating speed. The cross-sectional area of the material on the belt depends on the shape of the belt, namely on the adopted type of roller assembly and on the belt width. In addition, the real cross-sectional area of the bulk material on the belt depends on the way of dosing the material on the belt.

In order to determine the operating width of the belt (in meters) depending on its full width (B), the following expression is used:

$$(1) \quad b = 0,9 \cdot B - 0,05.$$

Geometrical parameters of the rollers were determined depending on the adopted type of roller assembly and the calculation of the cross-sectional area of the material on the belt was conducted.

Based on the required transport capacity, the belt width was determined according to the cross-sectional area of the material on the belt, operating speed and the bulk mass. The check was performed in relation to the size of the pieces of transported material. Necessary belt width was calculated based on (2):

$$(2) \quad B = 1,1 \cdot \left(\sqrt{\frac{Q}{v \cdot \rho \cdot k \cdot k_{\beta}}} + 0,05 \right)$$

where:

Q – is required capacity,

v – is transport speed,

ρ – is bulk density of the material,

k – is the coefficient that depends on the angle of pouring the material on the belt,

k_{β} – is the reduction coefficient that depends on inclination angle of the conveyor regarding the horizontal.

When defining the operating speed, some advice must be taken into account. It is often suggested to reduce the width of the belt and increase its speed accordingly. Increasing the speed causes a reduction in the drive load and tensile forces, which can result in the reduction of the weight of the conveyor and the reduction of the

cost of transport. On the other hand, the question arises as to the justification of higher speeds with regard to the technical and exploitation conditions of the conveyor operation. It has been established that, for higher speeds and small belt widths, its motion is sometimes unstable, with more intensive spillage of the material from the conveyor, but also with the increased wear of the belt and the bearings.

In order to drive a belt conveyor, the power of the drive motor must overcome all the resistances that occur during transport from:

- lifting of the material,
- friction in carrying roller bearings on loaded (working) and unladed (non-working) parts,
- friction in bearings of the drive, tension, deflection and bending drum,
- bending of the belt,
- unloading - loading devices and
- resistance to the motion of the belt over the rollers.

The belt conveyor design meets the two basic problems: necessity to provide a drive with enough power to start the conveyor even under adverse conditions and to ensure that the maximum force acting on the conveyor is within safe limits.

Traction force calculation can be performed using an orientation or detailed procedure. Recently, many theoretical and experimental tests have been performed with the aim of more accurate calculations of resistance forces. The conveyor contouring procedure is used to determine the traction force. It consists of numbering the characteristic points of the closed contour of the conveyor in the direction of motion of the traction element, starting from the point with the least tensile force. The tensile force at each subsequent point is equal to the tensile force at the previous point increased by the magnitude of the resistance force between those points:

$$(3) \quad F_{(i+1)} = F_i + W_{i+(i+1)}$$

where:

$F_i, F_{(i+1)}$ – are the tensile forces in subsequent contour points (i) and ($i+1$),

$W_{i+(i+1)}$ – is resistance force between the points (i) and ($i+1$).

The calculation includes determination of the values of each resistance, taking into account the known technical-exploitation parameters of the conveyor. For example, expression for resistances on a rectilinear loaded working section of the conveyor is in the form presented by [4]:

$$(4) \quad W_p^{RO} = \omega \cdot g \cdot [(q_M + q_{VE}) \cdot L_h^{RO} + q_r^R \cdot L^{RO}] \pm (q_M + q_{VE}) \cdot g \cdot H^{RO}$$

where:

ω - is the coefficient of resistance to motion of belt across the carrying roller

q_M - is specific mass of transported material,

q_{VE} - is specific mass of the tractive element of conveyor,

L_h^{RO} - is the length of horizontal projection of the loaded working section,

L^{RO} - is the length of loaded working section,

H^{RO} - is the height of vertical projection of loaded working section.

Minimum belt tension in the upper branch of the conveyor is also verified according to condition of computationally permissible deflection of the belt in that part of the conveyor.

To ensure normal belt operating conditions, the drive drum must be selected correctly. Here, the following factors must be taken into account: the belt thickness and its bending stresses during crossing over drum, mean pressure between drum and belt, type and place of conveyor installation.

Minimal drum diameter is adopted depending on the number of belt layers, while the drum length was chosen in accordance with the adopted transport belt width. The adopted diameter of the drive drum must meet the following condition:

$$(5) \quad p_{sr} = \frac{F_o}{\mu} \cdot \frac{360}{\pi \cdot D \cdot B \cdot \alpha} \leq p_{doz}$$

where:

p_{sr} – is mean pressure between the drum and the belt,

F_o - is the traction force,

B – is the belt width,

D – is the diameter of the drive drum,

α – is the span angle,

μ – is the coefficient of friction between the drum and the belt,

p_{doz} – is allowable pressure between the drum and the belt.

The roller assembly is one of the most important elements on which the efficiency of the belt conveyor depends, and especially the life of the belt. The important requirements for idlers are proper support and protection for the belt and proper support for the material being conveyed. The design of the roller assembly mostly determines the size and character of the loads on the belt and rollers. It must be sufficiently strong and durable and must have as little mass as possible.

The following effects were taken into account during selection of the roller type: the load factor (which is proportional to the roller load and depends on the assembly type, bulk material mass, assembly step), the factor of operating conditions (which encompasses the character of conveyor design and the way of operation), the speed factor and influence of conveyed material.

The concept of calculations was based on DIN 22101 and FEM 2.124 standards [7-8].

The major steps in belt conveyor calculation were:

- definition of capacity of the conveyor,
- calculation of maximum belt tension required to convey the load,
- selection of belt,
- selection of drive pulley,
- determination of motor power,
- selection of idlers and their spacing.

The main technical parameters of the belt conveyor are: the capacity of transport, $Q=230$ t/h, the belt width, $B=800$ mm, and the belt velocity, $v=1.6$ m/s.

3. Design of the 3D model

Calculation of the belt conveyor has provided all data and dimensions of the belt conveyor elements. Subsequently, the modelling of elements and final assembly of the belt conveyor were conducted [5]. Designed 3D model of the belt conveyor was created using "Autodesk Inventor" software [9].

The model was created bearing in mind the order of the elements assembly into the final device. Most of the adopted elements (conveyor rollers, drive and tensioning device, bearings) are mounted on the carrying structure of the belt conveyor.

Appearance of the drive unit and the part of the carrying structure are shown in Fig 1.

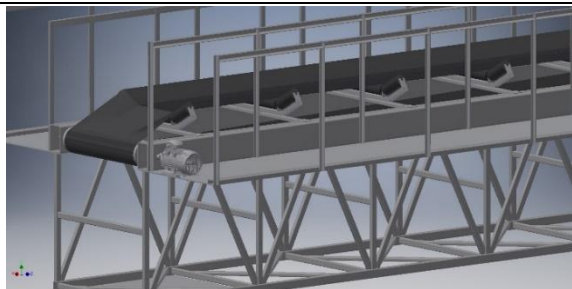


Fig. 1 Drive unit with carrying structure of the belt conveyor

Fig 2 presents the selected conveyor belt design. The tension pulley is located at the end of the belt conveyor.

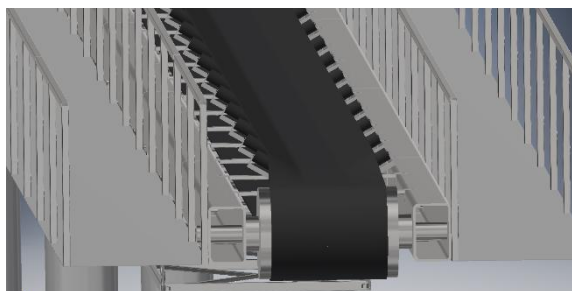


Fig. 2 Conveyor belt design.

Assembly with three carrying rollers was adopted in the paper. By reducing the length of the middle roller, it is generally possible to increase the lifetime of its bearings. However, due to need for unification and due to exploitation conditions, preference is given to roller assemblies with rollers of the same length. Thus, this solution was adopted in the paper (see Fig 3). Roller assemblies on the operating branch of the conveyor are presented in Fig 3.

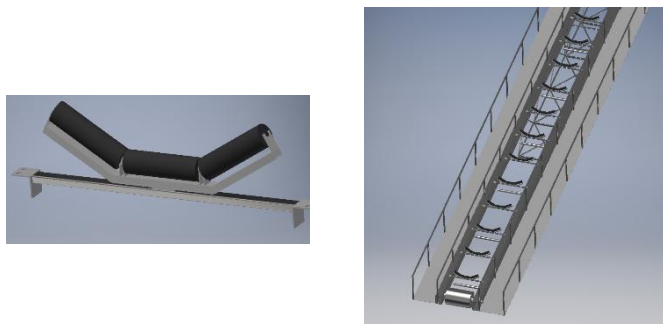


Fig. 3 Belt conveyor rollers (left) and basic carrying structure on the operating branch of the conveyor (right).

The overall model of the belt conveyor for continuous transport of bulk materials was obtained after all elements were assembled, and the result is shown in Fig 4.



Fig. 4 Overall model of the belt conveyor.

4. Conclusions

The belt conveyor is one of the most efficient conveyors. It is known as very configurable and easy to install.

The detailed calculation of the belt conveyor for conveying coal was conducted according to the design requirements and given transport capacity. The constant value of the tensile belt force during operation of the conveyor was used as foundation for calculations.

The conveyor dimensions obtained by calculations were used in 3D modelling of the conveyor. The used spatial modules of the software program have enabled the detailed analysis of deformations and stresses of the carrying structure of the designed belt conveyor.

To improve the design, the possible directions may include the creation of additional modules for research of the effects of variable belt tensile force and predicting the lifetime of the belts.

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Determining stress intensity factors of mode I for the crack in rectangular cross-section of thin-walled beam

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Abstract. A fracture mechanical behavior of thin-walled elements with through-thickness crack is researched. General analytical methods to determine stress intensity factors (SIF) in such elements are presented. The methods are based on the assessments of nominal stresses in the process of crack growth (first method) and change of inertia moment in defective section (second method). Correction functions are obtained for the central crack under bending for rectangular cross-section of thin-walled beams.

KEYWORD: THIN-WALLED BEAM, RECTANGULAR CROSS-SECTION, BENDING, CRACK, STRESS INTENSITY FACTOR.

1. Introduction

An important area of calculation is the prediction of the durability of machines and structures with fatigue cracks, using the methods of fatigue failure mechanics. These methods find practical application in mechanical engineering and construction, in relation to structural elements that are subject to time-variable loadings, and the period of operation of which after formation of the crack is important to assess the residual life of the machine or structure.

One of the promising areas of reducing the metal content and cost of load-bearing frame systems is the use of closed roll-welded profiles. Analysis of the operation of such structures in mobile machines, as well as in buildings shows that one of the main types of their load is cyclic bending loads with variable amplitude. Such loads in profiles fatigue contribute to cracks formation. Within linear fracture mechanics of materials, the study of the stress-strain state (SSS) of structural elements with crack is reduced to determining the stress intensity factor (SIF).

2. Theoretical Foundation

Analysis of methods for determining SIF for geometrically complex structural elements is given in [1, 2]. It is noted that such problems that take into account the real load and the geometry of the structure are quite complex in mathematical terms. To solve such problems analytical methods [2, 4], finite element method [1, 3, 6, 7], as well as computational and experimental methods [8] are used for each individual case of calculation; methods of the theory of thin-walled beams [9] or approximate engineering methods [10, 11] constituting an acceptable simplification of problems and transforming them into typical calculation schemes for which solutions are already known, and formulas for calculating of SIF are given in reference books [12, 13].

Following the analysis the approximate value of the SIF for a symmetrical through-thickness crack in a thin-walled rectangular element [10] is determined. The authors propose the following mathematical model of symmetrical crack development. The crack growth in the element is divided into several stages (Fig. 1): the propagation of a semi-elliptical crack in the horizontal wall, which gradually turns into a through-thickness crack, which develops along the horizontal wall (Fig. 1, a) (in this case SSS around the crack is close to the state, which occurs during tensile loading of a strip with a central crack, therefore we consider uniaxial tension of the strip with width equal to the length of the horizontal wall); crack propagation in the side walls (Fig. 1, b) (in this case SSS around the crack is close to the state that occurs during bending of a strip with an edge crack, so we consider bending of the strip with a thickness equal to the total thickness of the side walls). Thus, the development of a through-thickness crack in a closed profile is considered as two separate, unrelated tasks. In fact, the SIF is equal zero at the beginning of crack development in the side walls, and the influence of the previous stage of crack development on the next one is not estimated. The approximate SIF values are obtained, which allow to predict the crack size and to establish the allowable sizes of defects for the case of a symmetrical crack in the frame elements.

In this regard, we will consider the definition of SIF for closed roll-welded profiles using the following methods: method of nominal stresses (the problem is to determine σ_{nom} in a complex

profile with a crack) and method of the change of inertia moment in the defective profile with the crack developing in it based on dependences [8]. Using these methods, solutions to the problem of determining the SIF in open profiles with a crack are obtained, which coincide well with the results of experimental tests [14, 15]. In addition, the use of these methods allows creating a mathematical model of the defect in a thin-walled element, taking into account the influence of the previous stage of crack growth on the next one.

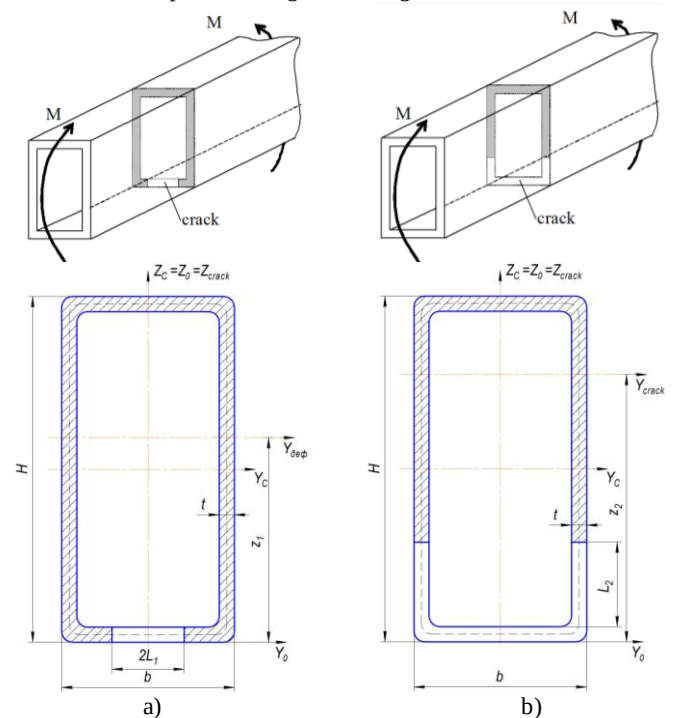


Fig. 1. Load scheme and Stages of a symmetrical crack growth in a closed rectangular profile:

a - in a horizontal wall; b - in vertical walls.

3. Methods of calculation

Method of calculation SIF using nominal stresses.

A central crack with length $2L_1$ develops in the closed rectangular profile in the lower edge.

The nominal stresses at the crack tip will be determined by the change in the inertia moment and in the coordinates of the center of mass of the net section of the rectangular profile. The change of vertical coordinate Z will have a significant effect, while the coordinate Y of the center of mass does not affect the nominal stresses, because it is a central crack.

For the first stage of crack development, the nominal stresses are determined by the dependences:

$$\sigma_1 = \frac{M(z_1 - t/2)}{I_{Y1}}, \quad (1)$$

$$z_1 = \frac{(b - 2t - 2L_1)t \frac{t}{2} + (b - 2t)t \left(H - \frac{t}{2}\right) + 2 \left((H - 2t)t \frac{H}{2}\right)}{(b - 2t - 2L_1)t + (b - 2t)t + 2t(H - 2t)}, \quad (2)$$

$$I_{Y1} = \frac{(b-2t-2L_1)t^3}{12} + (b-2t-2L_1)t\left(z_1 - \frac{t}{2}\right)^2 + \frac{(b-2t)t^3}{12} + (b-2t)t\left(H - z_1 - \frac{t}{2}\right)^2 + 2\left(\frac{t(H-2t)^3}{12} + t(H-2t)\left(z_1 - \frac{H}{2}\right)^2\right), \quad (3)$$

where z_1 – the distance from the lower edge of the profile (Y_0 axis) to the center of mass of the net section (running axis Y_{def}), m;
 I_{Y1} – inertia moment of the cross section of a closed profile with a crack, m^4 .

The other symbols are shown in Fig. 1.

When determining SIF, the problem is to load strip (using tension) weakened by a central crack of length $2L_1$ [12, 13]:

$$K_I^t = \sigma_1(1 - \varepsilon_1)\sqrt{\pi L_1} \cdot (1 + 0.128\varepsilon_1 - 0.288\varepsilon_1^2 + 1.525\varepsilon_1^3), \quad (4)$$

where $\varepsilon_1 = \frac{2L_1 t}{2(H-2t)t + 2(b-2t)t} = \frac{L_1}{(H-2t) + (b-2t)}$ – the ratio of the crack area to the gross cross-sectional area of the profile.

Substituting the dependences (1-3) in (4) and performing the transformation we obtain:

$$K_I^{(1)} = M \frac{H}{2} \frac{1}{I_Y} \sqrt{\pi L_1} F_1(\varepsilon_1), \quad (5)$$

where $L_1 = \varepsilon_1((H-2t) + (b-2t))$ – is determined by ε_1 ;

$M \frac{H}{2} \frac{1}{I_Y} = \sigma$ – nominal stresses in section of the profile without defects, MPa;

I_Y – the moment of inertia of the closed rectangular profile without defects, m^4 :

$$I_Y = 2\left(\frac{(b-2t)t^3}{12} + (b-2t)t\left(\frac{H}{2} - \frac{t}{2}\right)^2\right) + 2\frac{t(H-2t)^3}{12}. \quad (6)$$

For similar reasons for the second stage (Fig. 1, b) nominal stresses are determined by the dependences:

$$\sigma_2 = \frac{M(z_2 - \delta_1 - L_2)}{I_{Y2}}, \quad (7)$$

$$z_2 = \frac{(b-2t)t\left(H - \frac{t}{2}\right) + 2\left((H-2t-L_2)t \cdot \left(H - \left(\frac{H-2t-L_2}{2} + t\right)\right)\right)}{(b-2t)t + 2((H-2t-L_2)t)}, \quad (8)$$

$$I_{Y2} = \frac{(b-2t)t^3}{12} + (b-2t)t\left(H - z_2 - \frac{t}{2}\right)^2 + 2\left(\frac{t(H-2t-L_2)^3}{12} + 2t(H-2t-L_2)\left(z_2 - \left(H - \left(\frac{H-2t-L_2}{2} + t\right)\right)\right)^2\right). \quad (9)$$

When determining the SIF for a crack propagating in the wall of the profile, the problem is to bend the strip weakened by the edge crack L_2 [12, 13]:

$$K_I^b = \sigma_2(1 - \varepsilon_1)^2 \sqrt{\pi\left(L_2 + \frac{b-2t}{2}\right)} \times (1.122 - 1.40\varepsilon_2 + 7.33\varepsilon_2^2 - 13.08\varepsilon_2^3 + 14\varepsilon_2^4), \quad (10)$$

$$\text{where } \varepsilon_2 = \frac{L_2 + \frac{b-2t}{2}}{(H-2t) + (b-2t)}. \quad (11)$$

Substituting dependences (7-9) in (10) and performing the transformation we obtain:

$$K_I^{(2)} = M \frac{H}{2} \frac{1}{I_Y} \sqrt{\pi\left(L_2 + \frac{b-2t}{2}\right)} F_2(\varepsilon_2), \quad (12)$$

where L_2 is determined from dependence (11).

To approximate the correction functions $F_1(\varepsilon_1)$ (first stage) and $F_2(\varepsilon_2)$ (second stage) and obtain a generalized function $F_{1,2}^{(\sigma)}$, consider the assortment of bent welded profiles according to ДСТУ Б В.2.6-8-95 [16]. As it was shown in calculations, roll-welded profiles can be divided into three groups according to the ratio of height and width of their cross section: rectangular profiles with aspect ratio of 2:1, with ratio (1,375...1,475):1 and square profiles. Correction functions $F_{1,2}^{(\sigma)}$ are approximated by generalized curves:

– for rectangular profiles with an aspect ratio of 2:1:

$$F_{1,2}^{(\sigma)} = 1 + 4.131\varepsilon - 508.952\varepsilon^2 + 29523.311\varepsilon^3 - 864650.909\varepsilon^4 + 1.561 \cdot 10^7 \varepsilon^5 - 1.891 \cdot 10^8 \varepsilon^6 + 1.609 \cdot 10^9 \varepsilon^7 - 9.902 \cdot 10^9 \varepsilon^8 + 4.509 \cdot 10^{10} \varepsilon^9 - 1.540 \cdot 10^{11} \varepsilon^{10} + 3.972 \cdot 10^{11} \varepsilon^{11} - 7.746 \cdot 10^{11} \varepsilon^{12} + 1.134 \cdot 10^{12} \varepsilon^{13} - 1.226 \cdot 10^{12} \varepsilon^{14} + 9.483 \cdot 10^{11} \varepsilon^{15} - 4.966 \cdot 10^{11} \varepsilon^{16} + 1.576 \cdot 10^{11} \varepsilon^{17} - 2.290 \cdot 10^{10} \varepsilon^{18} \quad (13)$$

(the error of $F_{1,2}^{(\sigma)}$ when $0 < \varepsilon \leq 0.55$ does not exceed 2% for profiles with a height of 63–250 mm in the whole range of their thicknesses);

– for rectangular profiles with aspect ratio (1,375...1,475):1:

$$F_{1,2}^{(\sigma)} = 0.671 + 17.404\varepsilon - 257.773\varepsilon^2 + 2009.491\varepsilon^3 - 7759.120\varepsilon^4 + 14052.424\varepsilon^5 - 7366.370\varepsilon^6 - 8583.184\varepsilon^7 + 8859.089\varepsilon^8 \quad (14)$$

(the error of $F_{1,2}^{(\sigma)}$ when $0 < \varepsilon \leq 0.6$ does not exceed 4% for profiles with a height of 63–250 mm in the whole range of their thicknesses);

– for square profiles:

$$F_{1,2}^{(\sigma)} = 0.975 + 4.249\varepsilon - 121.681\varepsilon^2 + 1686.699\varepsilon^3 - 9730.664\varepsilon^4 + 27366.606\varepsilon^5 - 37796.230\varepsilon^6 + 22037.075\varepsilon^7 - 2292.681\varepsilon^8 \quad (15)$$

(the error of $F_{1,2}^{(\sigma)}$ when $0 < \varepsilon \leq 0.6$ does not exceed 10% for profiles with a height of 63–200 mm in the whole range of their thicknesses).

Generalized correction functions $F_{1,2}^{(\sigma)}$ for roll-welded profiles are presented in Fig. 2.

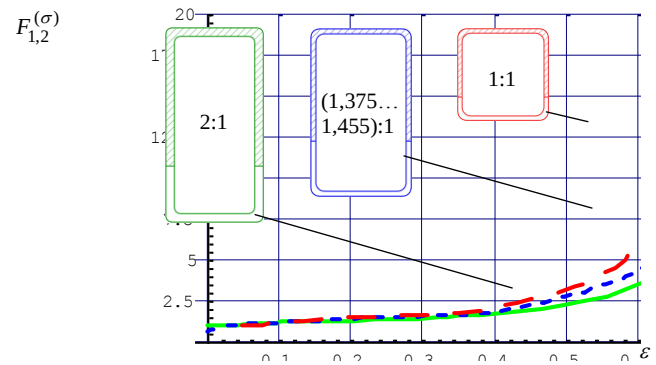


Fig. 2. Generalized correction functions $F_{1,2}^{(\sigma)}$ for a series of standard rectangular profiles

The expression to determine the SIF for a crack with length $0 < L < \left(\frac{b}{2} + H\right)$ will look like:

$$K_I^{(\sigma)} = M \frac{H}{2} \frac{1}{I_Y} \sqrt{\pi \cdot L} \cdot F_{1,2}^{(\sigma)}. \quad (16)$$

Method of calculation using the change of the inertia moment

Considering the energy parameters during crack propagation, namely the rate of energy release during crack propagation and making transition from energy to force characteristics - Irwin's criterion, the dependence of SIF for cracks developing in simple beam samples are obtained [8].

$$K_I = M \sqrt{\frac{1}{t} \left(\frac{1}{I_{Ydef}} - \frac{1}{I_Y} \right)}, \quad (17)$$

where M – bending moment, N·m;

t – thickness of beam, m;

I_{Ydef}, I_Y – inertia moments of beams with and without defect respectively, m⁴.

Consider the determination of SIF for a crack that develops in a thin-walled closed profile. With the development of a crack in the lower edge of a closed profile (first stage) (Fig. 1, a), the inertia moment of the defective profile is determined by the dependences (1-3), and the defect-free profile is defined by formula (6).

Then SIF during the development of crack in the edge of a closed profile is determined by the formula:

$$K_I^{(1)} = M \sqrt{\frac{1}{t} \left(\frac{1}{I_{Y1}} - \frac{1}{I_Y} \right)}. \quad (18)$$

Transforming SIF expression into standard form we obtain next dependence:

$$K_I^{(1M)} = \sigma \sqrt{\pi L} F_{1M} = M \frac{H}{2} \frac{1}{I_Y} \sqrt{\pi L} F_{1M}. \quad (19)$$

Similarly, for the second stage, the inertia moment of the defective profile will be determined by the dependences (7-9), and the SIF for the crack:

$$K_I^{(2)} = M \sqrt{\frac{1}{t} \left(\frac{1}{I_{Y2}} - \frac{1}{I_Y} \right)}. \quad (20)$$

Transforming SIF expression into standard form we obtain next dependence:

$$K_I^{(2M)} = M \frac{H}{2} \frac{1}{I_Y} \sqrt{\pi \left(L_2 + \frac{b-2t}{2} \right)} F_{2M}. \quad (21)$$

The expression to determine the SIF for a crack with length $0 < L < (b/2 + H)$ will look like:

$$K_I^{(M)} = M \frac{H}{2} \frac{1}{I_Y} \sqrt{\pi \cdot L} \cdot F_{1,2}^{(M)}. \quad (22)$$

Expressions of functions F_{1M} and F_{2M} are not given due to their cumbersomeness.

Defining the correction functions F_{1M} and F_{2M} for a series of standard profiles, we find generalized functions $F_{1,2}^{(M)}$ similarly to the one described above. Therefore,

– for rectangular profiles with an aspect ratio of 2:1:

$$\begin{aligned} F_{1,2}^{(M)} = & 0.877 - 8.567\varepsilon + 211.646\varepsilon^2 + 4755.803\varepsilon^3 - 310552.056\varepsilon^4 + \\ & + 6.829 \cdot 10^6 \varepsilon^5 - 8.767 \cdot 10^7 \varepsilon^6 + 7.515 \cdot 10^8 \varepsilon^7 - 4.572 \cdot 10^9 \varepsilon^8 + \\ & + 2.043 \cdot 10^{10} \varepsilon^9 - 6.833 \cdot 10^{10} \varepsilon^{10} + 1.727 \cdot 10^{11} \varepsilon^{11} - 3.305 \cdot 10^{11} \varepsilon^{12} + \\ & + 4.754 \cdot 10^{11} \varepsilon^{13} - 5.055 \cdot 10^{11} \varepsilon^{14} + 3.852 \cdot 10^{11} \varepsilon^{15} - \\ & - 1.989 \cdot 10^{11} \varepsilon^{16} + 6.230 \cdot 10^{10} \varepsilon^{17} - 8.931 \cdot 10^9 \varepsilon^{18} \end{aligned} \quad (23)$$

(the error of $F_{1,2}^{(M)}$ when $0 < \varepsilon \leq 0.6$ does not exceed 6% for profiles with a height of 63–250 mm in the whole range of their thicknesses);

– for rectangular profiles with an aspect ratio (1,375...1,475):1:

$$\begin{aligned} F_{1,2}^{(M)} = & 0.598 + 11.516\varepsilon - 71.371\varepsilon^2 - 5574.037\varepsilon^3 + 115501.304\varepsilon^4 + \\ & + 13100.877\varepsilon^5 - 2.681 \cdot 10^7 \varepsilon^6 + 4.341 \cdot 10^8 \varepsilon^7 - 3.791 \cdot 10^9 \varepsilon^8 + \\ & + 2.177 \cdot 10^{10} \varepsilon^9 - 8.819 \cdot 10^{10} \varepsilon^{10} + 2.603 \cdot 10^{11} \varepsilon^{11} - 5.674 \cdot 10^{11} \varepsilon^{12} + \\ & + 9.140 \cdot 10^{11} \varepsilon^{13} - 1.075 \cdot 10^{12} \varepsilon^{14} + 8.970 \cdot 10^{11} \varepsilon^{15} - \\ & - 5.035 \cdot 10^{11} \varepsilon^{16} + 1.705 \cdot 10^{11} \varepsilon^{17} - 2.630 \cdot 10^{10} \varepsilon^{18}; \end{aligned} \quad (24)$$

(the error of $F_{1,2}^{(M)}$ when $0 < \varepsilon \leq 0.6$ does not exceed 7% for profiles with a height of 63–250 mm in the whole range of their thicknesses);

– for square profiles:

$$\begin{aligned} F_{1,2}^{(M)} = & 0.206 + 20.20\varepsilon + 654.38\varepsilon^2 - 34866.31\varepsilon^3 + 387097.794\varepsilon^4 + \\ & + 4.590 \cdot 10^6 \varepsilon^5 - 1.775 \cdot 10^8 \varepsilon^6 + 2.397 \cdot 10^9 \varepsilon^7 - 1.959 \cdot 10^{10} \varepsilon^8 + \\ & + 1.096 \cdot 10^{11} \varepsilon^9 - 4.42 \cdot 10^{11} \varepsilon^{10} + 1.314 \cdot 10^{12} \varepsilon^{11} - 2.912 \cdot 10^{12} \varepsilon^{12} + \\ & + 4.801 \cdot 10^{12} \varepsilon^{13} - 5.807 \cdot 10^{12} \varepsilon^{14} + 5.006 \cdot 10^{12} \varepsilon^{15} - \\ & - 2.911 \cdot 10^{12} \varepsilon^{16} + 1.023 \cdot 10^{12} \varepsilon^{17} - 1.643 \cdot 10^{11} \varepsilon^{18}. \end{aligned} \quad (25)$$

(the error of $F_{1,2}^{(M)}$ when $0 < \varepsilon \leq 0.5$ does not exceed 8% for profiles with a height of 70–200 mm in the whole range of their thicknesses; – for square profiles with cross-section area 63×63 mm the error is 9.7 %).

Generalized correction functions $F_{1,2}^{(M)}$ for roll-welded profiles which are obtained using the change of inertia moment of the defective and defect-free section are presented in Fig. 3.

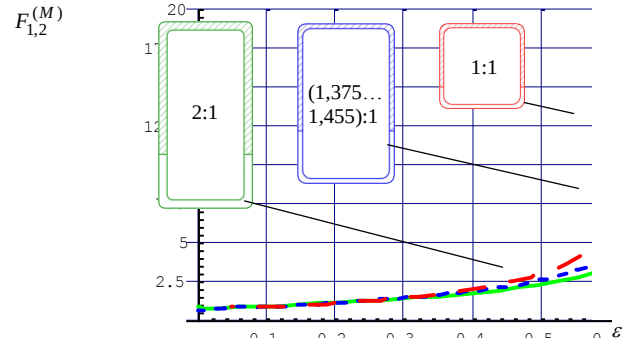


Fig. 3. Generalized correction functions $F_{1,2}^{(M)}$ for a series of rectangular thin-walled profiles

For comparison the generalized correction functions $F_{1,2}^{(\sigma)}$ and $F_{1,2}^{(M)}$ for a series of standard rectangular box profiles are given (Fig. 4), which are obtained by two methods: using nominal stresses and using the change of inertia moment of the defective element. The analysis shows that for all three groups of thin-walled roll-welded profiles there is a satisfactory agreement between the correction functions defined by the proposed methods. While $0 < \varepsilon \leq 0.6$ the error does not exceed 2% for rectangular profiles with an aspect ratio of 2:1, 4% – with an aspect ratio of (1,375...1,455):1 and 8,5% for square profiles. It should be noted that in all cases $F_{1,2}^{(\sigma)}$ is greater than $F_{1,2}^{(M)}$.

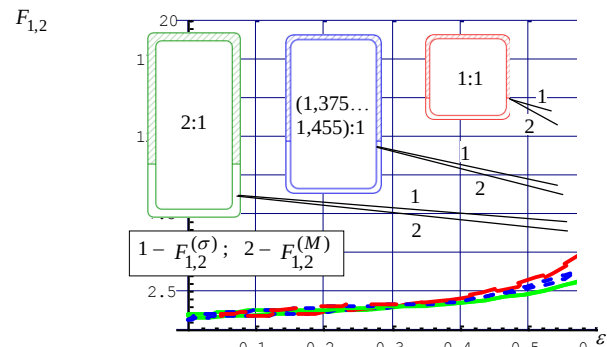


Fig. 4. Generalized functions $F_{1,2}^{(\sigma)}$ and $F_{1,2}^{(M)}$ for standard roll-welded box profiles with a crack

The analysis of correction functions shows that it is possible to determine the general correction functions $F_{1,2}^{(\sigma)}$ and $F_{1,2}^{(M)}$ for all assortment of roll-welded closed profiles when $0 < \varepsilon \leq 0.4$:

$$F^{(\sigma)} = 0.939 + 3.734\varepsilon - 14.115\varepsilon^2 + 35.856\varepsilon^3 - 21.447\varepsilon^4, \quad (26)$$

$$F^{(M)} = 0.769 + 1.219\varepsilon - 0.047\varepsilon^2 + 18.606\varepsilon^3 - 21.929\varepsilon^4. \quad (27)$$

The correction functions (26) and (27) are substituted into the expressions for determining the SIF (16) and (22), respectively.

To correctly compare the results of the SIF calculation using nominal stresses and using the change of inertia moment with the data of other authors (Fig. 5) we move from the relative parameter ε to the absolute parameter such as the actual crack length L , m. The results of SIF for a square thin-walled pipe 140x140x5 mm with a central crack (Fig. 1, a) for the case of pure bending at the value of initial stresses equal to 109 MPa were compared.

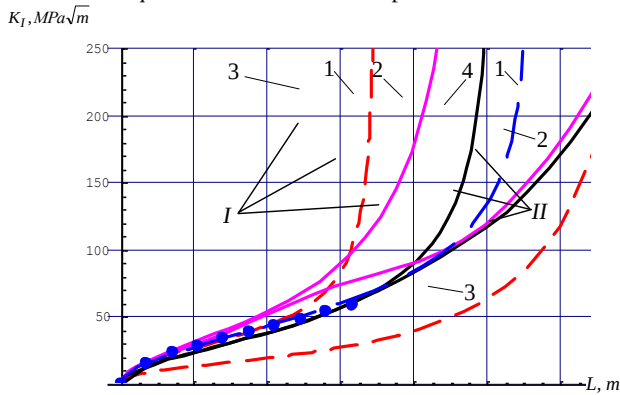


Fig. 5. Comparison of theoretical and experimental SIF values for central cracks in bars with square section $140 \times 140 \times 5$ mm:

... - FEM data [3]; 1 - calculation using nominal stresses; 2 - calculation using the change of inertia moment; 3 - calculation using [10]; 4 - calculation using [3]; I - the stage of crack development in the horizontal wall; II - the stage of crack development in the vertical wall.

The discrepancy between the results of the calculation of SIF by different methods was defined as

$$\Delta(K_{I(i)}) = \left| \frac{K_{I(base)} - K_{I(i)}}{K_{I(base)}} \right| \cdot 100\% \quad (28)$$

where the initial SIF $K_{I(base)}$ is the results of the analytical calculation of SIF for the central crack in the wall of a square thin-walled pipe, obtained in [3].

The results of the calculation of the discrepancy $\Delta(K_{I(i)})$ between the SIF values $K_{I(base)}$ using basic method, SIF values obtained in [1] and by the authors of this article (formulas 16 and 22) for a square thin-walled pipe $140 \times 140 \times 5$ mm are presented in table 1.

Table 1 - Results of SIF calculation obtained by different methods for a crack in a thin-walled square pipe $140 \times 140 \times 5$ mm

ε [3]	0.05	0.1	0.15	0.2	0.25	0.3
L , mm	7	14	21	28	35	42
K_I [3]	15.44	22.48	28.39	33.89	39.28	44.74
K_{Iexp} [3]	15.91	23.14	28.92	33.98	39.04	43.38
$\Delta(K_{Iexp})$, % [3]	3,04	2,94	1,87	0,27	0,61	3,04
K_I [10]	8.3	11.25	13.53	15.63	17.76	20.02
$\Delta(K_I)$, % [10]	46,24	49,96	52,34	53,88	54,79	55,25
$K_I^{(a)}$	16.64	23.87	30.33	37.52	45.67	54.29
$\Delta(K_I^{(a)})$, %	7,77	6,18	6,83	10,71	16,27	21,35
$K_I^{(M)}$	12.36	19.53	23.73	29.48	34.72	39.35
$\Delta(K_I^{(M)})$, %	19,95	13,12	16,41	13,01	11,61	12,05

Continuation of Table 1

ε [3]	0.35	0.4	0.45	0.5	0.6	0.7
L , mm	49	56	63	70	84	98
K_I [3]	50.44	56.53	63.22	70.79	90.49	125.53
K_{Iexp} [3]	48.44	54.22	59.28	—	—	—
$\Delta(K_{Iexp})$, % [3]	3,97	4,09	6,23	—	—	—
K_I [10]	22.52	25.36	28.66	32.55	43.02	59.59
$\Delta(K_I)$, % [10]	55,35	55,14	54,67	54,02	52,46	52,53
$K_I^{(a)}$	62.62	70.06	76.4	81.95	94.18	115.45
$\Delta(K_I^{(a)})$, %	24,15	23,93	20,85	15,76	4,08	8,03
$K_I^{(M)}$	45.34	52.77	60.49	68.53	89.11	113.05
$\Delta(K_I^{(M)})$, %	10,11	6,65	4,32	3,19	1,53	9,94

It should be noted that the engineering calculation of the SIF by formula (16) (nominal stress method) at the initial stage of development of the central crack (when $\varepsilon \leq 0.2$) has a good agreement with the basic method. When $0.2 < \varepsilon \leq 0.7$ a method based on the change of inertia moments (formula 22) has greater accuracy.

4. Conclusions

Using approximate methods in engineering such as nominal stresses method and method based on the changes of inertia moment in the defective cross-section the correction functions for determining the SIF for the central crack during bending of roll-welded thin-walled closed profiles are determined. The obtained results are compared with known theoretical and experimental data. The obtained results are the basis for further construction of mathematical models for the determination of SIF in corner cracks of roll-welded box profiles.

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Development of mechanism and machine mechanics in Belarus and interaction with Bulgarian scientific and engineering centers and associations

Part 1. Gear drives and power transmissions

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Abstract: Main directions and trends of mechanism and machine mechanics developing in Belarus are considered. Results of investigations fulfilled in the Joint Institute of Mechanical Engineering and V.A. Bely Metal Polymer Research Institute of NASB, Belarusian National Technical and Belarusian-Russian Universities, as well as in Belarusian State Transport University and other Belarusian research centers are presented. Generally, these investigations are forwarded for modernization of drives of various machines and mechanisms, including mobile machines, instrument mechanisms and estimation of their operation characteristics in the frame of "Industry 4.0" conception. The paper is divided into two parts. The first part focuses on gears and powertrains. Parts of the paper contain sources of information and main publications of Belarusian scientists. Thus, the paper as a whole bears informational and bibliographic character.

KEYWORDS: GEAR DRIVES, TRANSMISSIONS, DYNAMICS, RELIABILITY, VIBRATION

1. Introduction

Power transmissions contain various components (gears, bearings, shafts, friction elements, spline joints, etc.) with different conditions and types of loading, damage and limiting states. For determination of vehicle transmission loads, it is necessary to consider the dynamic model of a mobile machine including many aggregates that interact with the transmission.

Gear shifting, clutch and propulsion slips, engine disconnection and other modes and actions change the state of the dynamic system of the transmission and the machine, the composition of the working components and their loading conditions. During transient processes (starting, gear shifting, braking with the participation of the transmission), changes in the direction of the power flows passing through the transmission mechanisms, the occurrence of dynamic loads, which significantly exceed the quasi-static level, are possible.

The operating conditions of mobile machines and the driver's actions vary significantly from machine to machine, which leads to a dispersion of the load indicators of the transmission and the lifetimes of its components. In addition, there is a wide variety of structural, schematic and design solutions of the transmission, its gearboxes and other units. Because of this, the transmission of a mobile machine is one of the most methodically complex objects of technology for calculation and design. The methods of its calculation and design are of general machine-building significance and application, especially in terms of dependability calculations and dynamic calculations of multi-element loaded systems.

This Part 1 contains main scientific ideas of the Belarusian school of calculation and design of transmissions of mobile machines, the founder of which is the corresponding member of the Belarusian Academy of Sciences Igor Tsitovich (1917–1985), as well as the results of other Belarusian specialists on certain issues related to gearboxes and transmissions.

Modern results are also presented, which obtained within the framework of "Lifetime Mechanics of Machines", including the development of information models (digital twins) of transmissions.

2. Belarusian scientific school on gears and transmissions

2.1. Construction of the theory of transport and traction machines based on dynamic models of their interacting units

For the correct design of the transmission and other units of a mobile machine, it was proposed to build a new theory of transport and traction machines based on the dynamic models of their interacting units [1].

An important position of the theory is the need to form a computational dynamic model before developing a mathematical model of transmission and vehicle dynamics, as well as the

possibility of creating their electronic dynamic models without constructing differential equations.

Within the framework of this theory, the interaction of the engine, transmission, suspension, brake system and other systems should be described [2, 3].

One of the theoretically significant and practically important issues is the determination of the maximum dynamic loads of the transmission.

The monographs [2], [4] provide unique information, including the parameters of the dynamic schemes of the main cars and trucks produced in the USSR, as well as methods and results of calculating the maximum dynamic loads and natural vibration frequencies of transmissions on gears (monograph [4] is dedicated to the memory of Igor Tsitovich).

The bases of the vehicle theory became essentially new approach that considers dynamic processes of the transmission and vehicle as multibody dynamics. This theory including methods of modeling of reactive links of units in dynamics models, for example, under interaction of transmission and vehicle suspension [4]. Figure 1 shows mechanical models for determining the dynamic load of the transmission. In this case, E = elastic links of the transmission, e = elastic links of the suspension, J = rotating masses of the engine, transmission, driving wheels and vehicle equivalent (J_5), m_1 = sprung mass are designated.

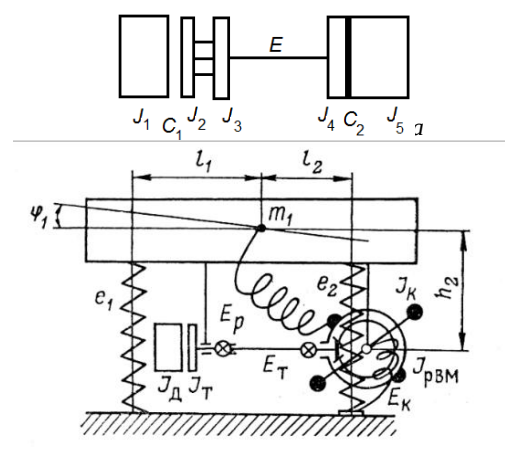


Fig. 1. Mechanical models for determining dynamical load of a transmission during vehicle starting: a = single shaft model, b = multilink model that reproduces the transmission-suspension interaction

2.2. Statistical regularities of the load mode of vehicle transmissions

Numerous experiments have been carried out, experimental data on loading conditions have been generalized, and characteristic distributions of loads on the semi-axes of mobile machines have

been obtained. Specific tractive forces (STF) were used to describe loading. Entering and analyzing STF as dimensionless parameter made it possible to establish patterns in the load modes of various types of mobile machines. Typical curves of STF for mobile machines of various classes were constructed [5].

It was shown that within the selected classes of cars, it is possible to use universal curves of STF, and in calculations for durability, one can pass from them to quasi-static loads on different parts of the vehicle (gear wheels, bearings). The dynamic components of the loads are taken into account in the calculations of parts by the coefficients of internal and external dynamic loads. As a result, a set of parameters was identified, according to which it is recommended to calculate the load mode for a general transport vehicle and its transmission [6].

2.3. Development of probabilistic calculations of machine parts

There are known proposals to use for probabilistic calculations the generalized data, obtained by "mixing" the load distribution curves for individual conditions (taking into account their shares) into a common (generalized) curve. It is shown that such proposals are wrong. The approach of the scientific school of Igor Tsitovich is that to construct a correct probabilistic calculation, it is necessary to take into account the variation of loads from machine to machine [1].

In dissertation [7] executed under the direction of Igor Tsitovich it is offered to use **average value of specific traction effort** for describing a severity (heaviness) of operation conditions. Thus the variety of operation conditions can be described by distribution of the given parameter, and every operation condition gives its load distribution curve.

In practice calculations the load distribution curve can be replaced by the calculated load and the **run factor** (mileage coefficient). This factor described the damaging effect of the load curve at a certain limit state relative to the design load. The run factors were determined for typical load curves in advance by the ratio of the average and calculated loads (P_p/P_{cp}) (Fig. 2). In this case, the variation of the load curves is reproduced in the form of the distribution of the run factor.

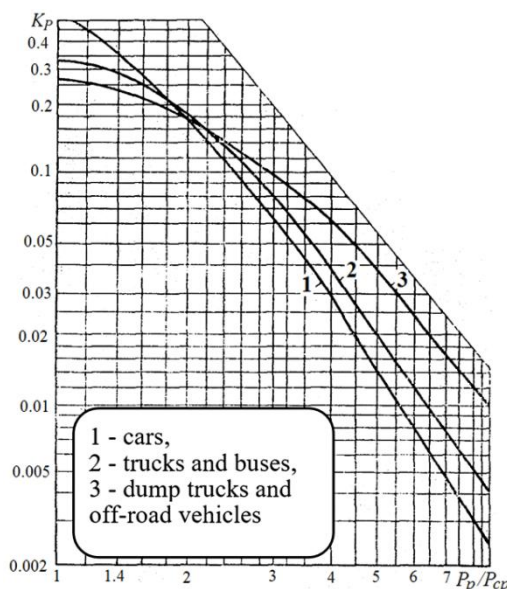


Fig. 2. Graphs to determine the run factors for contact stresses (exponent for the fatigue curve $m = 3$) [8]

This approach made it possible to bring probabilistic calculations to real computational practice. In the beginning, the deterministic calculation with use of the run factor is carried out. Then calculated measures of load-carrying ability R and extent of damage for one km q serve as reference points for construction of distributions of these parameters. Random character q is determined by a random value of the run factor, and random character of the $R = f(\sigma_r)$ is

determined by a random value σ_r . This parameter is a characteristic of the load carry ability, for example, the endurance limit of a part.

The lifetime (mileage) is also a random value and is determined as

$$L = R/q \quad (1)$$

The probabilistic calculation has been brought to practical use under the assumption that the distributions of R and q are logarithmic normal distributions. This assumption is confirmed by experimental studies. Then L is also distributed according to this law. The distribution parameters L are determined by the corresponding parameters of the distributions R and q . The distribution L is used to find the reliability indicators of a machine part on the considered limiting state.

For the main parts of the transmission (gears, bearings, spline joints and others), methods of calculation for variable loads and computer calculation programs were developed [6, 8, 9].

2.4. Using probabilistic calculations in practice

The results were recognized in the USSR and abroad, were included into state standard documents of the USSR [10], [11]. In motor industry of the USSR the supervising document has been accepted for a choosing and calculating the rolling bearings [12], where loading factors are applied instead of run factors.

Until now, these approaches, described in the educational and reference literature [13], [14], [15], [16], published in the USSR, are used in the educational process and in the practice of design.

2.5 Direction "Vibration monitoring of mobile machine transmissions"

At present, improving the reliability and significantly increasing the lifetime of machines, mechanisms and equipment is not possible without the wide use of methods and tools for technical diagnostics. Solving this problem contributes to the development of a method of vibration-pulse diagnosis of gears. This method is based on the analysis of parameters of vibration impulse, synchronized with the rotation diagnosed gears, with the identification of the harmonic components of vibration impulse multiple of the tooth meshing frequency and are in the region of the resonant frequencies of the mechanism. These components stimulate the most intense vibrations, by changing the parameters which determine the technical condition of gears under variable loading-speed modes of their work. This makes it possible to create systems for on-board diagnostics and forecasting the remaining life of elements of transmission units of mobile machines in operation [17]–[19].

The results obtained are used in the creation of methodological and instrumental tools for diagnostics of drive mechanisms and transmission systems operating in various operating conditions (i.e., both in quasi-stationary modes of operation, and in conditions of variable speeds and loads), in relation to heavy-duty and specialized equipment produced by BELAZ, MZKT, etc.

3. Modern stage: Lifetime mechanics of machine

3.1. The features of the Lifetime mechanics of machines

Development of the Igor Tsitovich school (ITS) results in modern stage can be presented as a scientific direction "Lifetime mechanics of machines" (LMM). The features of the LMM and its integrating role in assessing the lifetime and functional properties of technical items are in Fig. 3 [23].

LMM integrates the approaches of strength mechanics (force, stress, damage), multibody dynamics, reliability theory, system theory, and computer technologies. The use of a computer involves more than just the use of technologies based on digitalization. It is essential to take into account the peculiarities of using a computer as a discrete computing device for simulating real analog processes of mobile machines, for example, fast-flowing processes when shifting transmission gears.

The traditional reliability theory deals with systems consisting of the depersonalized components, which are described by the set of

reliability indexes. Engineering operates with stresses of machine parts, and sometimes with their lifetimes. Dependences of components which take place at mechanical level are not reproduced in the traditional theory of reliability. That leads to erroneous results in evaluating machine reliability.

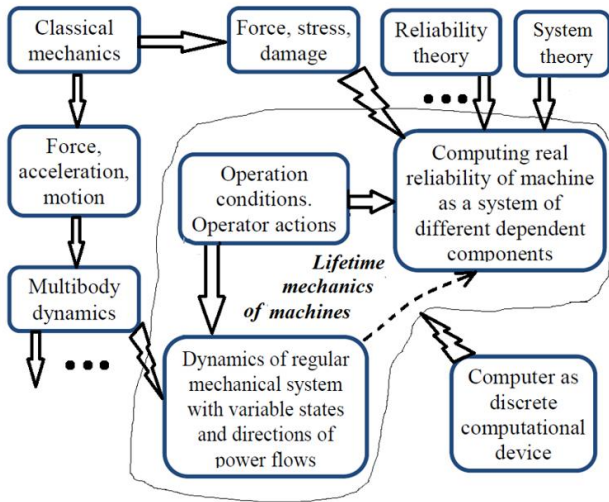


Fig. 3. LMM and its integrating role

LMM gives novel approaches and techniques for calculation of machine reliability, since mechanical levels and finishing by structural levels, with consideration of complicated logic of limiting states for machine components (parts, units, assemblies, and so on) and for the machine as a whole (Fig. 4) [22], [24]. The dependent behavior of elements is taken into account when calculating the real reliability of machines and other complex systems.

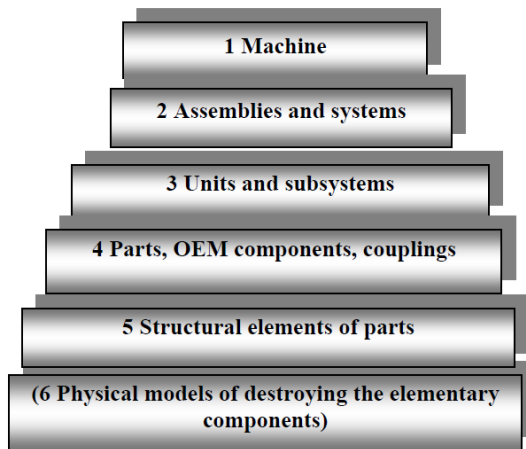


Fig. 4. Levels of machine presentation as hierarchical system [24]

Modern mechanical objects can change their configurations or states, for example, under the action of friction forces or external and internal factors. As result the direction of power flows in the object varies. Typical representatives of such systems are vehicle transmissions.

The important practical problem for such objects is determination of the loads acting on their elements. The object behavior (dynamics, functional properties) and its loading (damage/destruction, lifetime) are interconnected. Therefore, it makes sense to investigate problems of determination of functional and lifetime properties in a single direction "Lifetime mechanics of machines".

The ideas of ITS are reflected in a number of provisions of the LMM. Five highlights (1–5) are presented below [20], [21].

1. The need to form a computational dynamic model before the development of mathematical models of the transmission and vehicle (ITS, subsection 2.1) is reflected in the concept of a regular mechanical system, which contains the rules for constructing correct

mechanical systems for simulating analog dynamic processes of a mechanical system with variable states using a computer as a discrete computing device (LMM, [22], [23]);

2. The bases of the vehicle theory including methods of modeling of reactive links of units in dynamics models, for example, under interaction of transmission and vehicle suspension (ITS, subsection 2.1, Fig. 1) are reflected in methods for *typification of translational and rotational subsystems* of vehicle, as well as in the universal mathematical models of vehicle and their components, containing the indicators of state, for clutches, brakes and other devices with variable structure (LMM, [23], [25], [26], [27]);

3. Statistical regularities of the load mode of vehicles and their transmissions (ITS, subsection 2.2) and methods of their use in practical calculations of transmissions (ITS, subsection 2.3, Fig. 2) were transformed in more general representation of operation conditions in the form of a probabilistic spectrum of relative durations of standard conditions, and were added with classification and the use of various driving styles in calculations of lifetime for mechanical components (LMM, [23], [24]);

4. Probabilistic calculations of the main transmission parts (tooth gears, bearings) on the basis of the universal loading modes and representation of lifetime calculations with use of typical laws of distribution for relative lifetime (ITS, subsection 2.3) have served as prerequisites to creation of essentially new types of calculations of real reliability of parts, assembly, units, and the vehicle as a whole on the basis of the principle of dependent behavior of elements in the loaded mechanical system (LMM, [23], [24], [28]);

5. The first State Standard of the USSR in the field of prognosis of item reliability during designing [10], guidelines by calculation of machine-building components [11], [12] and others (ITS, subsection 2.4) received a respective response in the modern State Standards of Republic of Belarus in a field of dependability of technically complicated items (TCI) (LMM [29] – [32]).

Details of historically significant data on IST and the new LMM direction are given in [20].

3.2. LMM and digitalization

Digitalization provides new opportunities for individualizing the technical condition of the product in operation. The evolution of concepts, which led to the now accepted term "Digital Twin" (DT) and its modern interpretation, is presented in the works of M. Grievez [33], [34].

Many publications analyze various interpretations of this concept and give their own definitions. In some cases, a statistical analysis of formal features from known publications is used. The analysis of such publications, taking into account the topic of gears and transmissions, is given in [35], [36]. Based on such publications, the following conclusion can be made: the term DT has become quite familiar, and specialists at the subconscious level are usually understood it unambiguously, but when defining this concept, they generate a lot of formulations.

Within the framework of the RMM, the vision and understanding of the information model as a DT of a technically complex object (TSI) begins with the paper [37], that developed the idea of academic A. Ershov about the need for an information model of the machine [38]. The paper [15] contains the proposition that the creation and use of science-intensive products should be based on new information technology. The technology involves the development of an information model at all stages of the life cycle of the machine.

The information model should be included in the technical documentation accompanying the machine and allow the use of various sources: semantic, structural (logical), parametric (quantitative, mathematical) models; measurement results; expert evaluations; means of simulating the elements and units of the machine (in slow, accelerated and real time scales in relation to the current, retrospective and predicted state).

The following aspects are essential:

- each part of the machine is represented as a source of information signals;

- the machine units in which it is possible and appropriate to implement the principles of reflexive control are allocated (the control object and the controlling part change functions at some point);
- procedures for identifying information sources, control objects and reflex-ive nodes are provided, their interrelationships are determined nodes are provided, then their interdependences are determined.

The information model should be designed in such a way as to allow the use of various sources:

- semantic, structural (logical), parametric (quantitative, mathematical) models;
- measurement results;
- expert evaluations;
- means of simulating the elements and units of the machine (in slow, accelerated and real time scales in relation to the current, retrospective and predicted state).

Thus, the mentioned methodology anticipated the basic principles of Industry 4.0: the model approach and creation of the digital twin.

Basic features. With regard to a mobile machine and its transmission, the features associated with the construction of the information model can be summarized as follows:

- 1) a plurality of system representations (a complex of symbolic types and models covering kinematics, dynamics, reliability, resource consumption),
- 2) a description and consideration in the development of the transmission of the operating environment of the machine and the operator's actions (a model of operating conditions taking into account its variability - a probabilistic representation),
- 3) individualization (including on the basis of diagnosis and assessing the resource consumption of a specific product).

The **new developed principles** cover [23], [35], [36]:

- sharing synthesis, analysis and multi-criteria estimates of the transmission;
- interaction of mechanical models of materials and reliability theory;
- consideration of a transmission as a multicomponent system with variable states and variable power flows depending on the mode of their operation;
- unity of component loading modes (principle of dependent behavior of components in a loaded system);
- localization of loading in damage models of their simplest components;
- construction of diagnostic models using condition assessment by an integral criterion and predictive calculation based on monitoring the accumulation of transmission damage.

The following **basic systemic representations** are used for transmissions: regular mechanical system, structural diagram, kinematic diagram, dynamic diagram, normalized dynamic diagram, scheme of limiting states and scheme of faults.

The principles of schematization are developed for the transition from a real mechanical object to its symbolic representation using a regular mechanical system. For the universal representation, formalization and automation of equations in the field of kinematics and dynamics, a universal mapping of differentials and gears is used, which, along with the display of shafts, controls and a frame, allows the correct schematization of transmissions and gears of any kind with standard and non-standard elements. For the mathematical description of objects structures, the developed canonical matrix and structurally-distributive matrix are used.

3.3. Peculiarities of TCI state monitoring in operation

Individualization of TCI and its information model (Digital Twin) from stage "making and assemblage" is presented in Fig. 5 [39]. These are the supplied components; used equipment and personnel (the stage of making and assemblage); the operation conditions, the operator(s) of TCI, the maintenance (the stage of operation).

The current level of development of sensors and computer facilities also allows recognizing the state of the environment and

transferring data for management systems and forecasting models that use data from the environment. In this case, the environment model also refers to the TCI digital twin.

When installing the sensors, the principle of minimum multiplicity should be adhering. Sensors, even in the minimum number, should reflect the force and speed constituents of the unit operation modes. In the ideal case, a one sensor can be used to obtain a load (force) spectrum, by which the load processes of all the limiting components are reconstructed.

Since it is not always possible to install a sensor to generate a signal about the loading the limiting element, the task of reconstructing local loads of limiting elements arises. To solve it, models that allow to reconstruct the stresses (or other loads) of the limiting elements from the signals of existing sensors, should be developed and used.

It is rational to use the data on the loading in the form of general power flows, and individualize the loads for the limiting components to conduct when considering their limiting states.

The feature of the developed diagnostic method is using conceptual modeling the oscillating process for the gear drive and the propagation of vibrations in the transmission [35], [36], [39]. It is advisable to applicate together integral diagnostic models and predictive ones based on damage accumulation (Fig. 5, block "State models"). Such a "two-coordinate" approach (from two points of view) ensures a higher veracity of the individual lifetime forecast.

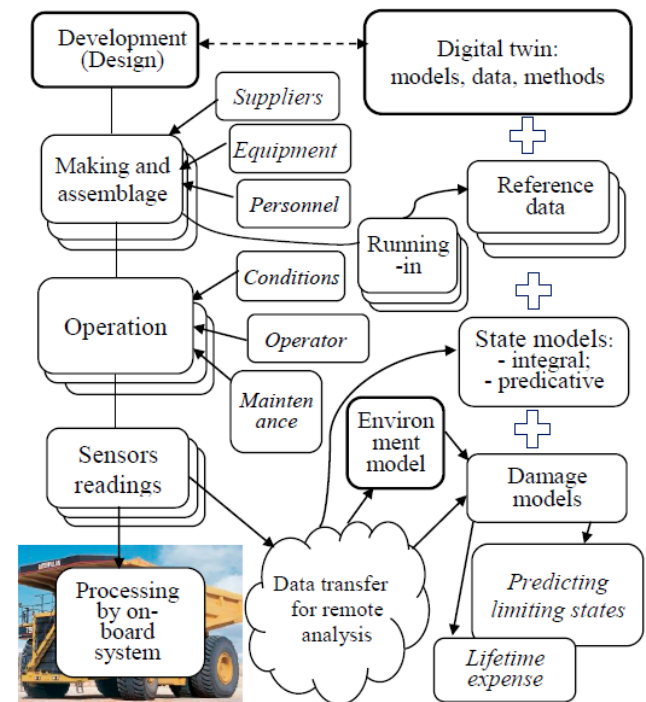


Fig. 5. Individualization of an item and its information model (Digital twin) from stage "making and assemblage".

The main variable individual component of any transmission unit is the level of its internal dynamic loading. Changes in this level are due to the peculiarities of the manufacture of the unit and the operating conditions of the machine, which includes the transmission unit. The most sensitive components to changes in the internal dynamic load of the unit are gears and bearings. The greatest damage to the clutches is associated with short-term transient processes, which requires individual monitoring of the modes of these processes.

The feature of the developed diagnostic method is using conceptual modeling the oscillating process for the gear drive and the propagation of vibrations in the transmission [35], [36].

An example of the implementation of the described approach is presented below. The reducer of a motor-wheel (RMW) of a mining dump truck with installed sensors is shown in Fig. 6. The main processes for the emergence, transformation and processing of

signals in the RMC and its monitoring system are shown in Fig. 7. Details, concerning this approach, are in [39].

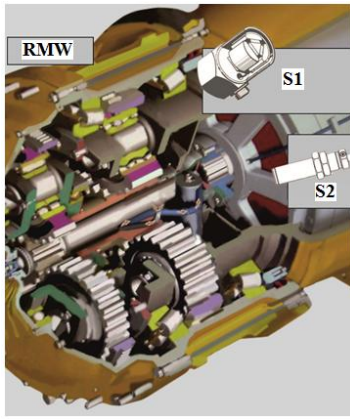


Fig. 6. RMW with sensors

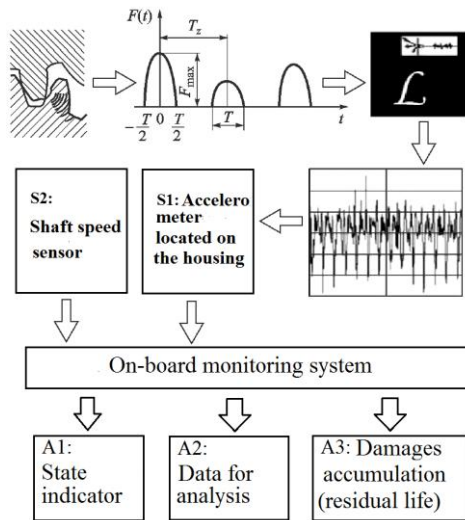


Fig. 7. Processes in the RMW and its monitoring system

Some of the above provisions on vibration monitoring the state of spur gears of drives of the TCI for assessment of their residual lives have been included to State Standard of Republic of Belarus [32].

3.4. New concept and method for assessment of lifetime expense of TCI

A new approach based on the concept of "lifetime expense" is proposed to personalize the state of TCI.

The concept of the term "consumption of lifetime" for the single component is obvious, as well as the understanding of its additional term "residual life". The assessment of the state of life for a complex object, consisting of several components, is ambiguous. And besides, some components can be replaced or repaired.

To eliminate this uncertainty and evaluate this property, the term "lifetime expense" for TCI is introduced, as well as a new indicator. This indicator has a sense of the life potential of the TCI and is determined as follows

$$K_A = \xi_1 K_{P1} + \xi_2 K_{P2} + \dots + \xi_n K_{Pn}$$

where K_{Pi} = lifetime expense of the i th main part of the TCI (presented as relative value); ξ_i = the weight factor that determines the contribution of the main part to the total lifetime expense of the TCI. It is proposed to consider ξ_i as the relative mass of the main part (the fraction of this part mass in the total mass of n parts that determine the TCI lifetime) [36, 40].

The next fundamental point is lifetime expense of the main part:

$$K_P = 1 - (1 - K_L)(1 - K_T)$$

where K_L = lifetime expense by length (mileage, operating time); K_T = lifetime expense by time (age); K_L relates to damage processes under loads during working; K_T relates to damage processes under time (ageing processes).

The values of K_L and K_T are determined at the time of monitoring / evaluating the technical condition of the TCI. Usually, the processes responsible for K_L and K_T can be considered as independent. Then, K_L can be interpreted as the probability of failure in the running hours (under the influence of loads in the duty cycle), and K_T as the probability of failure in age (time). Then K_P is the probability of failure of the main part of the TCI under the combined action of loads and age at the considered time.

The developed methodology is realized in the State standard of the Republic of Belarus [31].

Formulas for typical calculations of the lifetime expense of transmission and other units of mobile technics as well as examples of calculations are given in [31, 40].

Fig. 8 shows the graphs K_L , K_T , and K_P . It is estimated that 100% lifetime expense by age occurs over 30 years. The same period corresponds to 100% lifetime expense by length (mileage). This case is illustrative; in real practice, the full expenditure of the lifetime in mileage and age, as a rule, is not simultaneously achieved.

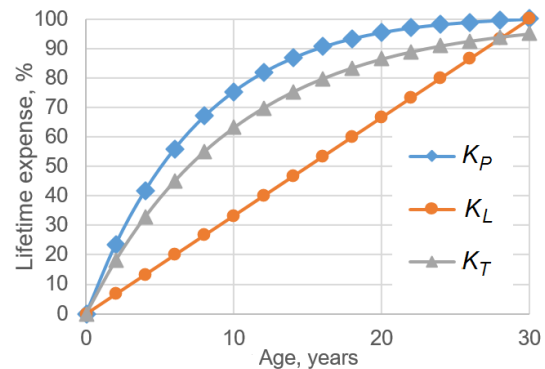


Fig. 8. Lifetime expense K_P for linear law K_L and exponential K_T [36]

4. Conclusions

In the development of the Belarusian scientific school, created by Corresponding Member of the Academy of Sciences of the BSSR Igor Tsitovich (1917–1985), the following periods can be distinguished: the first, initial (1960–1985), when Igor Tsitovich was directly involved in R&D; the second one (with 1985) when the LMM has been formed, and the third (informational) period connected with development of information model of the transmission as a technically complicated item.

A set of representations and methods developed for transmissions can be considered as typical in a methodical sense for mechanical objects and combined objects, the basis of which are mechanical systems. Many of them are universal and can be applied to a wide range of technical items. They have been implemented in practice, in educational, industrial and research activities.

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Walking pattern generation and control for a bipedal robot

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Abstract: Bipedal, four-legged and humanoid robots are rapidly increasing in our lives. The design and development of robots continue in similar. For this reason, the importance of studies on bipedal robots is also increasing. In this study, the design of a biped robot, forward and inverse kinematics computation were made. Bipedal robot walking pattern and joint angle changes were determined according to the kinematic model of the robot and the power of the motors to rotate the joints. As a result of the walking pattern, center of mass and zero moment point change were tracked. As a result of the study, the stepping style, walking motion, gait analysis, changes in joint angles were determined of a bipedal robot.

Keywords: BIPEDAL ROBOT, FORWARD- INVERSE KINEMATIC OF ROBOT, WALKING PATTERN,

1. Introduction

Studies on the controlled and computing of bipedal and humanoid robots have been continued by many researchers for the last 70 years, according to the number of degrees of freedom (DOF) and different design[1] [2]. The main aim of the designs is to improve the robot's movement abilities, and it is desired that robots have the attributes of thinking, moving, and making decisions with artificial intelligence. Kinematic methods are used for joint movements in the control methods of bipedal robots[3][4]. In many studies, the walking motion of the robot has been created according to forward and inverse kinematic solutions. In addition to kinematic movement, the center of mass (COM) must be followed and kept within certain limits in order for the robot to remain in balance in the walking pattern[5][6]. Tracking the (COM) with the zero-moment point (ZMP) is another important control factor. The position and power information of the motors that provide joint movements constitute another control part. The movement structures of bipedal and humanoid robots require a multidisciplinary study[7]. This study, it is aimed to design a biped robot, determine the joint movements required for walking movement and to establish the walking control loop.

In this paper, robot design, forward inverse kinematic calculations and joint movement of bipedal robot explained in section 2. In section 3, the motion control walking pattern is explained, it is completed with the conclusion and references.

2. Bipedal Robot Design and Kinematic Parameters

Kinematic solutions are essential for the control of biped robots[8]. The positions of the robot joints can be solved in two different ways using forward kinematic or inverse kinematic calculations via D-H (Denavit and Hartenberg) parameters[9]. With kinematic calculations, joint angles, target positions, singularities (singularity) and working area boundaries can be determined.

Forward kinematics is obtained by determining joint transformation matrices with the orientation of robot joint angles and positions from the main to lower end. This equation is the type of calculation in which the position angle motion relationship is determined. For the forward kinematic computation of the biped robot, the axis, angle and length values of the robot joints should be determined. In the study, the 3D model of the bipedal robot, the positions of the 6 axes on a single leg of the robot and the lengths of the joints are determined in figure 1. Based on this information, a table of DH parameters has been created and shown to obtain the transformation matrices of the joints in table 1. DOFs are shown in figure 1. Joint transformation matrices according to DH parameters are given in equations 1-5. The angle and positions change of the limbs during the walking locomotion can be determined with the 5th equation.

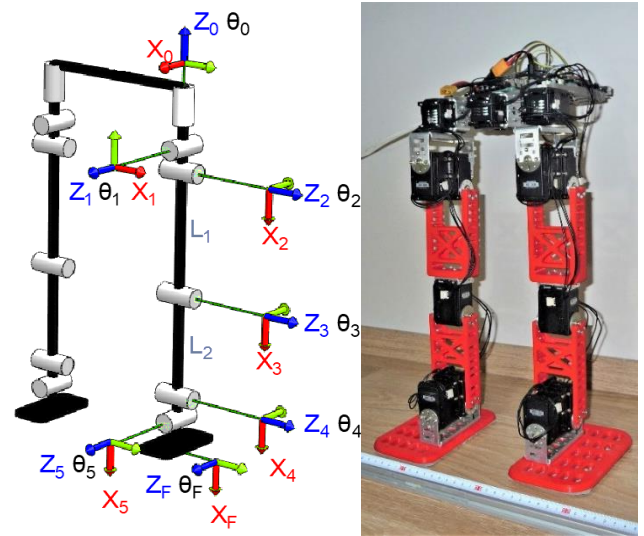


Fig. 1 Bipedal robot and coordinate frames

Table 1: Six DOF Left Leg D-H parameters.

int i	θ_i	α_i	a_i	d_i
0-1	0	90°	0	0
1-2	θ_1	-90°	0	0
2-3	θ_2	0°	L_1	0
3-4	θ_3	0°	L_2	0
4-5	θ_4	90°	0	0
5-F	θ_5	0°	0	0

$$[{}^0_1T] = \begin{bmatrix} \cos \theta_1 & -\sin \theta_1 & 0 & a_{1-1} \\ \sin \theta_1 \cos \alpha_{1-1} & \cos \theta_1 \cos \alpha_{1-1} & -\sin \alpha_{1-1} & -\sin \alpha_{1-1} d_i \\ \sin \theta_1 \sin \alpha_{1-1} & \cos \theta_1 \sin \alpha_{1-1} & \cos \alpha_{1-1} & \cos \alpha_{1-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$[{}^0_1T] = \begin{bmatrix} c \theta_3 & -s \theta_3 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ s \theta_3 & c \theta_3 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad [{}^1_2T] = \begin{bmatrix} c \theta_4 & -s \theta_4 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -s \theta_4 & -c \theta_4 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$[{}^2_3T] = \begin{bmatrix} c \theta_5 & -s \theta_5 & 0 & L_1 \\ s \theta_5 & c \theta_5 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad [{}^3_4T] = \begin{bmatrix} c \theta_6 & -s \theta_6 & 0 & L_2 \\ s \theta_6 & c \theta_6 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$${}^4_5T = \begin{bmatrix} c\theta_7 & -s\theta_7 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ s\theta_7 & c\theta_7 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^5_6T = \begin{bmatrix} c\theta_8 & -s\theta_8 & 0 & 0 \\ s\theta_8 & c\theta_8 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$${}^0_F T = [{}^0_1 T][{}^1_2 T][{}^2_3 T][{}^3_4 T][{}^4_5 T][{}^5_6 T] \quad (5)$$

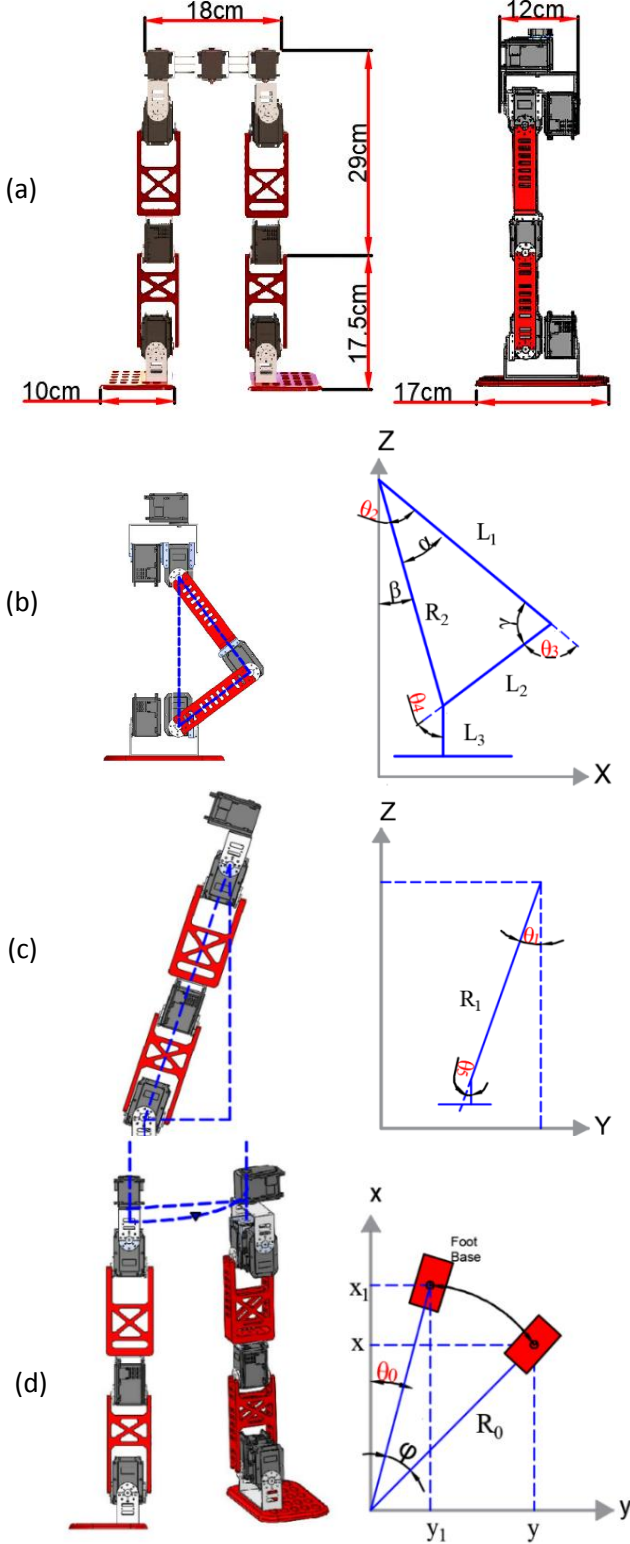


Fig. 2 Bipedal robot DOF views

The inverse kinematics is used for the computation of joint positions satisfying desired relative positions and orientations

between the body center and foot[10]. This method to base on determining the joint variables in terms of the end-effector position and orientation.

The inverse kinematic computation of the designed bipedal robot is calculated by using the trigonometric approach[11]. According to figure 2(a), joint angles and leg position information are obtained to calculate the changing during the walking motion of the bipedal robot via equations 6-11. Joint angles and positions of the robot leg are computed in the equations 6-8, from right-side view in figure 2(b). Figure 2 (c) shows the angle between the wrist and hip joints also the total length of the leg this relationship is explained by the equation.9. In figure 2(d), the position information is shown as a result of the robot leg rotating and its expressed in equation 11.

$$\gamma = \arcsin\left(\frac{L_2 \sin \alpha}{R_2}\right) \quad \beta = \arcsin\left(\frac{x_1}{R_2}\right) \quad (6)$$

$$\alpha = \arccos\left(\frac{L_1^2 + L_2^2 - R_2^2}{2L_1^2 L_2^2}\right) \quad (7)$$

$$\theta_2 = \alpha + \beta \quad \theta_3 = \pi - \gamma \quad \theta_4 = \theta_2 - \theta_3 \quad (8)$$

$$\theta_1 = \theta_5 \quad (9)$$

$$R_0 = \sqrt{x^2 + y^2} \quad \varphi = \arctan\left(\frac{y}{x}\right) - \theta_0 \quad (10)$$

$$x_1 = R_0 \cos \varphi \quad y_1 = R_0 \sin \varphi \quad (11)$$

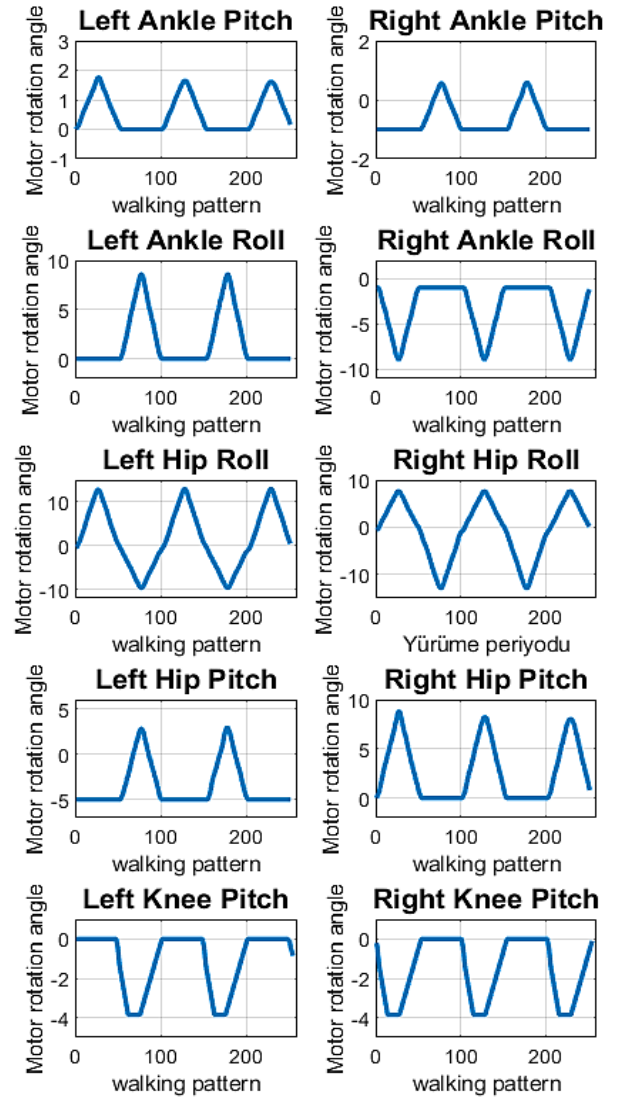


Fig 3. 10 DOF motor rotation angle in walking pattern

Figure 3 shows the joint angles of the bipedal robot according to the walking pattern. The walking cycle is determined according to inverse kinematic calculations, torque limits of motors and friction.

3. Locomotion Control and Walking Tracking

The walking pattern of biped robots consists of one leg and double leg phase. In order for the robot to move without tipping over, it must create a reaction moment against the overturning moment caused by COM[12] [13]. This reaction is created by the reaction force between the ground and the foot base. The position where the reaction force occurs on the foot is called the zero-moment point (ZMP)[14]. This position changes according to the single and double leg phases. In figure 6, the oscillation in the walking process of COM, ZMP reference trajectory and steps of the robot are shown. The ZMP location is limited by the distance between the robot's two-legs. When this limit value is exceeded due to COM, the robot can topple over[15][16]. In order not to exceed this limit, it is requisite to control the joint movements of a bipedal robot that cause the change of COM. We can show this relationship with the diagram in the figure.

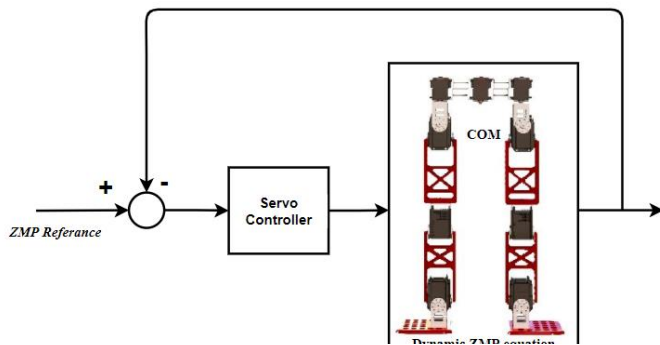


Fig. 4 ZMP COM control diagram

In the control diagram in Figure 4, the control software of the servo motors is designed and controlled on the OpenCM card. When the joint movements in Figure 3 are applied to the dynamixel mx64 servo motors, a walking pattern is obtained as in figure 6. In the steps pattern, the ZMP oscillation and COM trajectory information obtained from the gyro sensor appear in figure 7. When the projection of COM is examined, it is seen that it stays between the legs and walks on balance. The walking pattern in bipedal robots is similar to the walking pattern in humans. The human walking pattern appears in figure 5 [17].

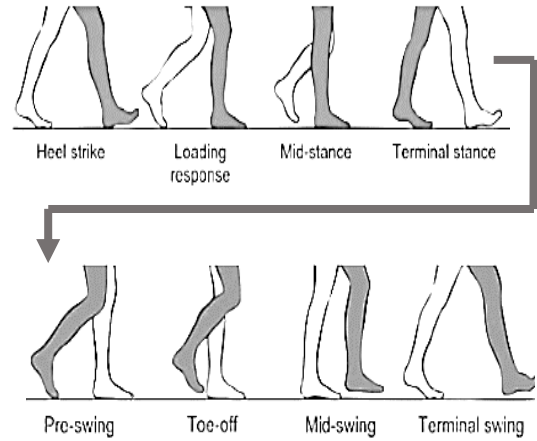


Fig. 5 Human walking cycle phases



Fig. 6 Bipedall robot walking phases

The figure 6 (a) shows the walking phase of moving the right foot of the bipedal to forward steps. in the figure (b) movement of moving the left foot to forward.

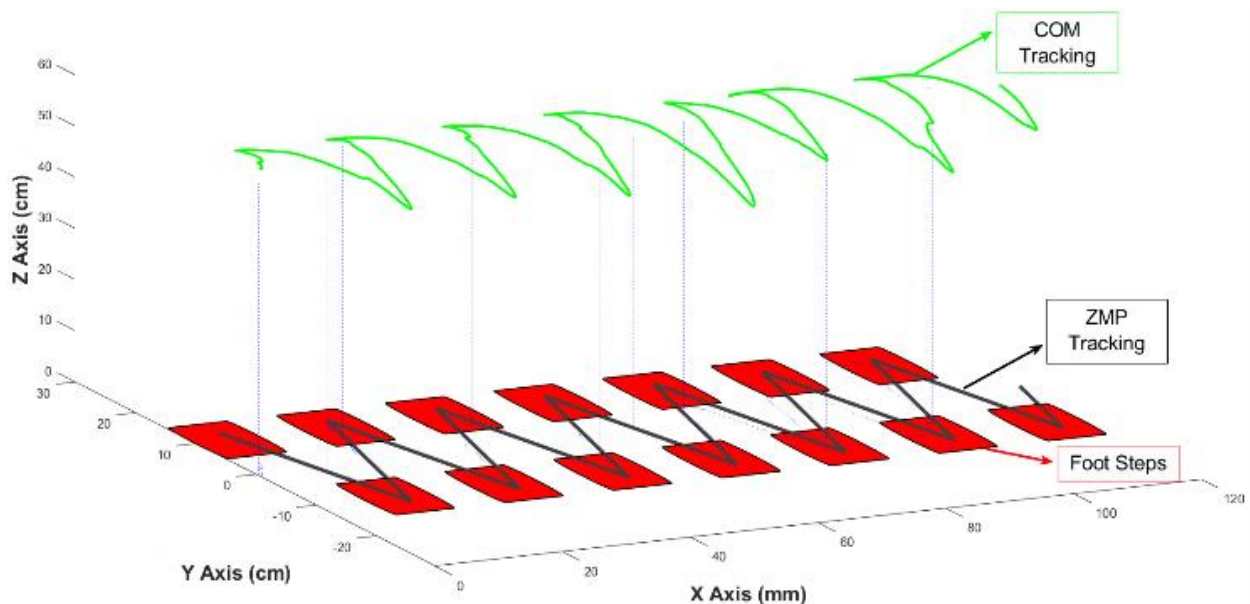


Fig. 7 COM and ZMP oscillation of bipedal robot in walking pattern

4. Conclusion

In this study, a bipedal robot is designed. Forward and inverse kinematic models are calculated. A walking style for ZMP and COM values were determined for gait and balance control. Walking styles in bipedal robots were wanted to be likened to be human walking styles, but due to motor torque values, angle limits were imposed on some joints. This angle limit also caused the walking style to be different. Better walking performances can be obtained with more powerful motors or smaller designs. The next study, it is aimed to expand the external factors that disturb the balance and the joint angle limits. In addition, it is aimed to perform locomotion trajectory control by measuring with sensors for ZMP tracking. As a result, an experimental bipedal robot that can walk at a speed of 4 cm/sec has been applied.

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Exergy analysis of base and optimized high pressure feed water heating system from nuclear power plant

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Abstract: In this paper is performed exergy analysis of high pressure feed water heating system and all of its components which operates in nuclear power plant. Four cases are observed: system operation in the base case and system operation in three optimized cases. Exergy analysis show that optimization by using different algorithms has a different influence on the exergy destructions, while all the algorithms increase whole system and its components exergy efficiencies. An increase in the ambient temperature increases exergy destructions and decrease exergy efficiencies of the whole observed system and its components, regardless of operation case. The highest exergy efficiency of the whole analyzed system is 96.12% and is obtained by using an IGSA algorithm at the lowest observed ambient temperature of 5 °C. By observing exergy destructions only, it should be noted that GA and IGSA algorithms give almost identical results.

KEYWORDS: FEED WATER HEATING SYSTEM, EXERGY ANALYSIS, OPTIMIZATION, AMBIENT TEMPERATURE CHANGE, NUCLEAR POWER PLANT

1. Introduction

Nowadays, any steam power plant has condensate/feed water heating system which is used for condensate/feed water heating during its return from the main steam condenser to steam generator [1]. Such heating systems can be simple or complex, what depends on the number of components and heating steam delivery to all of the components [2, 3].

Such systems increase efficiency of power plant in a way that it saves fuel used in steam generator (in comparison to power plants which did not possess such heating system) [4, 5]. As in conventional, condensate/feed water heating systems are also a constituent part of modern nuclear power plants [6].

In this paper is performed an exergy analysis of high pressure feed water heating system which is one part of complete condensate/feed water heating system in a nuclear power plant. Exergy analysis is performed by using operating parameters from base working regime, as well as from three optimized working regimes. The ambient temperature is also varied to get a complete picture about analyzed system operation. This analysis showed that all of the optimization algorithms increases exergy efficiency of high pressure feed water heating system and its components, while its performances significantly varies when compared exergy destruction change of each analyzed system component.

2. Description of the analyzed high pressure feed water heating system from nuclear power plant

The analyzed high pressure feed water heating system is located in nuclear power plant between deaerator and steam generator [7]. It consists of two closed regenerative feed water heaters (HPH1 and HPH2), Fig. 1. HPH1 is closer to the deaerator which means that it operates with lower steam pressures, while HPH2 is closer to steam generator and it operates with the highest steam pressures in the plant if compared to all other condensate/feed water heaters.

Condensate obtained from steam in HPH2 is returned to HPH1 (so in HPH1 can be used heat of that condensate for feed water temperature increase). After a feed water heating process in both heaters, condensate is returned to deaerator (operating point 6, Fig. 1). As can be seen from Fig. 1, operation principle of the analyzed high pressure feed water heating system and all of its components, is the same as for any other similar system (or component) from other steam power plants [8].

In Fig. 1 are also presented operating points required for the exergy analysis of this system and its components. Based on those operating points will be defined all the exergy analysis equations and will be presented all of the required steam/water operating parameters.

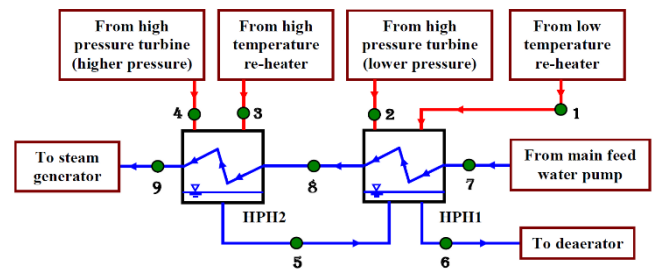


Fig. 1. High pressure feed water heating system from nuclear power plant along with required operating points

3. Equations for the exergy analysis

Overall exergy balance equations

Exergy analysis of any control volume or a system is defined by the second law of thermodynamics [9, 10]. For any control volume or a system in steady state, the main exergy balance equation can be defined, according to [11, 12], as:

$$\dot{X}_{\text{HEAT}} - P = (\sum \dot{m}_{\text{OUTLET}} \cdot \varepsilon_{\text{OUTLET}}) - (\sum \dot{m}_{\text{INLET}} \cdot \varepsilon_{\text{INLET}}) + \dot{E}_{\text{ex,D}}, \quad (1)$$

where P is power in (kW), $\dot{m}$ is operating medium mass flow rate in (kg/s) and $\dot{E}_{\text{ex,D}}$ in (kW) is exergy destruction (exergy power

loss) of a control volume or a system. In Eq. 1, $\dot{X}_{\text{HEAT}}$ in (kW) is the exergy transfer by heat at the temperature T , which is defined according to [13] by the following equation:

$$\dot{X}_{\text{HEAT}} = \sum (1 - \frac{T_0}{T}) \dot{Q}, \quad (2)$$

where T is temperature in (K), $\dot{Q}$ is heat transfer in (kW) and index 0 is related to the ambient state. The last undefined element from the Eq. 1 is specific exergy ε in (kJ/kg), which according to [14] is defined by an equation:

$$\varepsilon = (h - h_0) - T_0 \cdot (s - s_0), \quad (3)$$

where h is operating medium specific enthalpy in (kJ/kg) and s is operating medium specific entropy in (kJ/kg·K). Total exergy $\dot{E}_{\text{ex}}$ in (kW) of any fluid flow stream is [15]:

$$\dot{E}_{\text{ex}} = \dot{m} \cdot \varepsilon = \dot{m} \cdot [(h - h_0) - T_0 \cdot (s - s_0)]. \quad (4)$$

Overall definition of exergy efficiency η_{ex} for any system or a control volume is [16]:

$$\eta_{\text{ex}} = \frac{\text{CUMULATIVE EXERGY OUTLET}}{\text{CUMULATIVE EXERGY INLET}}. \quad (5)$$

Unlike energy analysis [17, 18], exergy analysis takes into account the ambient state (the ambient pressure and temperature) in

which control volume or a system operates. The ambient temperature change can have significant influence on the control volume or a system exergy efficiency and exergy destruction.

For the exergy analysis of observed high pressure feed water heating system and its components, will be presented only the main equations which define exergy destruction and exergy efficiency. These equations are based on the operating points (from 1 to 9) presented in Fig. 1.

HPH1 exergy destruction and efficiency

$$\dot{E}_{ex,D,HPH1} = \dot{m}_1 \cdot \varepsilon_1 + \dot{m}_2 \cdot \varepsilon_2 + \dot{m}_5 \cdot \varepsilon_5 + \dot{m}_7 \cdot \varepsilon_7 - \dot{m}_6 \cdot \varepsilon_6 - \dot{m}_8 \cdot \varepsilon_8, \quad (6)$$

$$\eta_{ex,HPH1} = \frac{\dot{m}_8 \cdot \varepsilon_8 - \dot{m}_7 \cdot \varepsilon_7}{\dot{m}_1 \cdot \varepsilon_1 + \dot{m}_2 \cdot \varepsilon_2 + \dot{m}_5 \cdot \varepsilon_5 - \dot{m}_6 \cdot \varepsilon_6}. \quad (7)$$

HPH2 exergy destruction and efficiency

$$\dot{E}_{ex,D,HPH2} = \dot{m}_3 \cdot \varepsilon_3 + \dot{m}_4 \cdot \varepsilon_4 + \dot{m}_8 \cdot \varepsilon_8 - \dot{m}_5 \cdot \varepsilon_5 - \dot{m}_9 \cdot \varepsilon_9, \quad (8)$$

$$\eta_{ex,HPH2} = \frac{\dot{m}_9 \cdot \varepsilon_9 - \dot{m}_8 \cdot \varepsilon_8}{\dot{m}_3 \cdot \varepsilon_3 + \dot{m}_4 \cdot \varepsilon_4 - \dot{m}_5 \cdot \varepsilon_5}. \quad (9)$$

Whole feed water heating system (WS) exergy destruction and efficiency

$$\dot{E}_{ex,D,WS} = \dot{m}_1 \cdot \varepsilon_1 + \dot{m}_2 \cdot \varepsilon_2 + \dot{m}_3 \cdot \varepsilon_3 + \dot{m}_4 \cdot \varepsilon_4 + \dot{m}_7 \cdot \varepsilon_7 - \dot{m}_6 \cdot \varepsilon_6 - \dot{m}_9 \cdot \varepsilon_9, \quad (10)$$

$$\eta_{ex,WS} = \frac{\dot{m}_9 \cdot \varepsilon_9 - \dot{m}_7 \cdot \varepsilon_7}{\dot{m}_1 \cdot \varepsilon_1 + \dot{m}_2 \cdot \varepsilon_2 + \dot{m}_3 \cdot \varepsilon_3 + \dot{m}_4 \cdot \varepsilon_4 - \dot{m}_6 \cdot \varepsilon_6}. \quad (11)$$

4. Operating parameters required for the analysis in a base and optimized working regime

Data for this analysis are taken from [7] where the authors presented optimization of the PWR (Pressurized Water Reactor) nuclear power plant by using three algorithms - GA (Genetic Algorithm) [19], SA (Simplex Algorithm) and a new improved hybrid algorithm IGSA (Improved Genetic-Simplex Algorithm). In Table 1 are presented operating parameters in the base nuclear power plant working regime required for the high pressure feed water heating system exergy analysis, while in Table 2, Table 3 and Table 4 are presented required operating parameters for the exergy analysis obtained using IGSA, GA and SA algorithms, respectively.

In each of four nuclear power plant working regimes, specific exergy for each operating point and at each observed ambient temperature is calculated by using Eq. 3. Required specific enthalpies and specific entropies for each fluid stream are calculated by using NIST-Refprop 9.0 software [20]. The ambient pressure is always equal to 1 bar.

Table 1. Operating parameters of steam/water in base working regime

Base				
O. P.	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Pressure (MPa)	Temperature (°C)
1	72.01	974.60	2.630	226.7
2	111.02	2597.90	1.910	210.0
3	79.30	1220.10	6.110	276.8
4	76.48	2652.40	2.760	229.2
5	155.78	897.40	2.705	209.8
6	338.81	745.90	1.871	176.1
7	1613.40	719.51	8.310	169.1
8	1613.40	873.11	8.179	203.1
9	1613.40	973.89	8.052	226.0

O. P. = Operating Point (in accordance to Fig. 1)

Table 2. Operating parameters of steam/water in working regime improved by IGSA algorithm

IGSA				
O. P.	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Pressure (MPa)	Temperature (°C)
1	86.41	995.40	2.850	231.1
2	133.22	2579.50	2.050	213.5
3	63.48	1269.70	7.040	286.3
4	77.02	2632.90	2.960	233.0
5	140.50	931.73	2.897	217.4
6	360.13	757.62	2.001	178.7
7	1653.30	731.38	8.310	171.8
8	1653.30	906.82	8.179	211.5
9	1653.30	1000.67	8.052	232.0

O. P. = Operating Point (in accordance to Fig. 1)

Table 3. Operating parameters of steam/water in working regime improved by GA algorithm

GA				
O. P.	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Pressure (MPa)	Temperature (°C)
1	83.07	994.30	2.840	230.9
2	133.17	2580.20	2.040	213.3
3	65.87	1267.60	7.000	285.9
4	72.12	2633.80	2.940	232.8
5	137.98	930.57	2.855	217.2
6	354.21	756.62	1.991	178.5
7	1647.70	730.34	8.310	171.6
8	1647.70	905.69	8.179	211.3
9	1647.70	995.36	8.052	230.9

O. P. = Operating Point (in accordance to Fig. 1)

Table 4. Operating parameters of steam/water in working regime improved by SA algorithm

SA				
O. P.	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Pressure (MPa)	Temperature (°C)
1	77.51	992.40	2.820	230.5
2	124.79	2582.10	2.020	212.9
3	70.65	1263.00	6.910	285.0
4	78.77	2635.80	2.920	232.4
5	149.42	919.43	2.863	214.7
6	351.72	754.81	1.976	178.1
7	1644.60	728.48	8.310	171.2
8	1644.60	894.76	8.179	208.8
9	1644.60	993.34	8.052	230.4

O. P. = Operating Point (in accordance to Fig. 1)

5. Results and discussion

Observing HPH1 exergy destruction, Fig. 2, it can firstly be concluded that increase in the ambient temperature increases HPH1 exergy destruction in any of four observed cases. It is interesting that all optimization processes increase HPH1 exergy destruction at any observed ambient temperature when compared to base working regime. The highest HPH1 exergy destructions at any ambient temperature can be seen for IGSA and GA optimized schemas.

Increase in the ambient temperature results also with an increase in HPH2 exergy destruction in any of four observed cases, Fig. 3. HPH2 (heater which operates with the highest steam pressures, mounted the closest to steam generator) was the main objective of the optimization procedure (regardless of used algorithm), because all of the algorithms decreases HPH2 exergy destruction. The lowest HPH2 exergy destruction, in comparison to base working

regime, is obtained by IGSA and GA - those two algorithms significantly decreases HPH2 exergy destruction (much more than SA). Exergy destruction values for HPH2 at any observed ambient temperature and for any observed case are much lower when compared to HPH1.

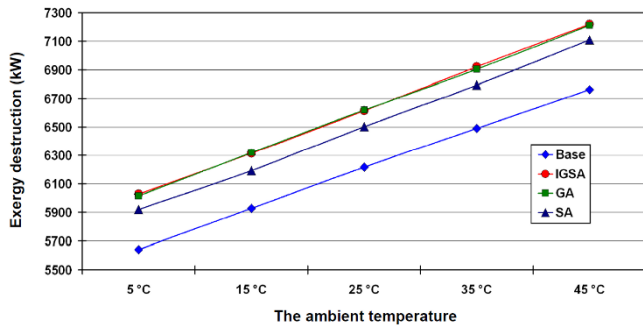


Fig. 2. Change in HPH1 exergy destruction in four observed cases for different ambient temperatures

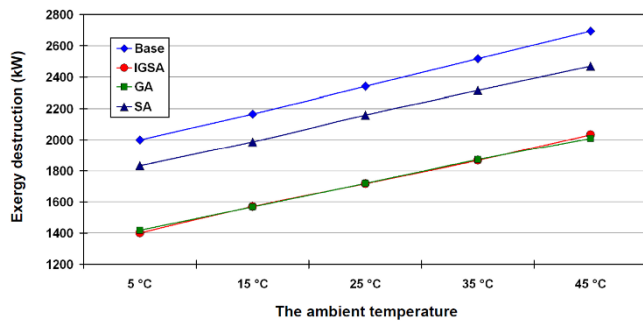


Fig. 3. Change in HPH2 exergy destruction in four observed cases for different ambient temperatures

As for both high pressure feed water heating system components, for the whole high pressure feed water heating system is also valid a conclusion that an increase in the ambient temperature increases exergy destruction in any of four observed cases, Fig. 4. For the whole observed heating system, usage of IGSA and GA decreases exergy destruction, while SA increases exergy destruction at any ambient temperature (in comparison to the base working regime). The lowest exergy destruction for the whole analyzed high pressure feed water heating system (between 7430 kW and 9250 kW at the ambient temperatures of 5 °C and 45 °C, respectively) is obtained using IGSA and GA algorithms, Fig. 4.

An increase in the exergy destruction of HPH1, during the increase in the ambient temperature, resulted with a decrease in the HPH1 exergy efficiency in all of four observed cases, Fig. 5. The lowest increase in HPH1 exergy efficiency (in comparison to base working regime) is obtained with SA, while the highest increase is obtained with IGSA (and is equal between 95.07% and 92.67% at the ambient temperatures of 5 °C and 45 °C, respectively). For HPH1, the GA gives almost the same results in exergy efficiency at each observed ambient temperature (only slightly lower than IGSA).

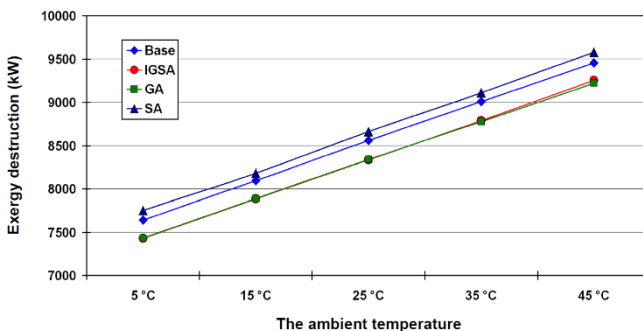


Fig. 4. Change in the exergy destruction of the whole observed high pressure heating system in four observed cases

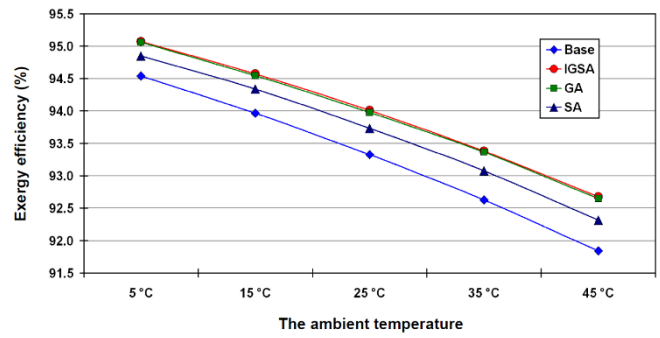


Fig. 5. Change in HPH1 exergy efficiency in four observed cases for different ambient temperatures

The ambient temperature increase also results with a decrease in exergy efficiency of HPH2 (as for HPH1) in all of four observed cases, Fig. 6. In a HPH2 exergy analysis is proved that IGSA gives the best results when compared to other algorithms. Therefore, the best obtained exergy efficiencies of HPH2 by using IGSA are between 97.98% and 96.45% at the ambient temperatures of 5 °C and 45 °C, respectively.

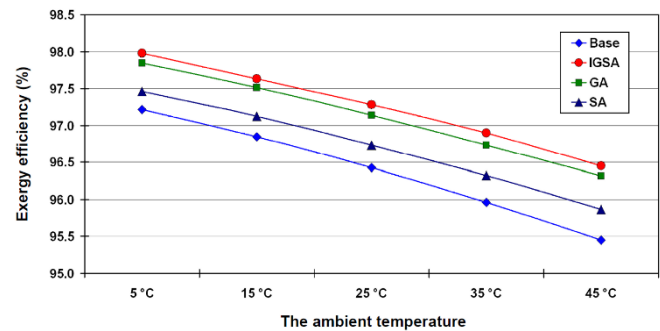


Fig. 6. Change in HPH2 exergy efficiency in four observed cases for different ambient temperatures

For the whole analyzed high pressure water heating system, is valid the same conclusion as for each of its components – increase in the ambient temperature decreases exergy efficiency, regardless of which case is observed, Fig. 7. The obtained exergy efficiencies of the whole high pressure feed water heating system by IGSA are between 96.12% and 94.06% at the ambient temperatures of 5 °C and 45 °C, respectively.

Further analysis of the observed high pressure feed water heating system and both of its components will also be based on the methods of artificial intelligence [21-28].

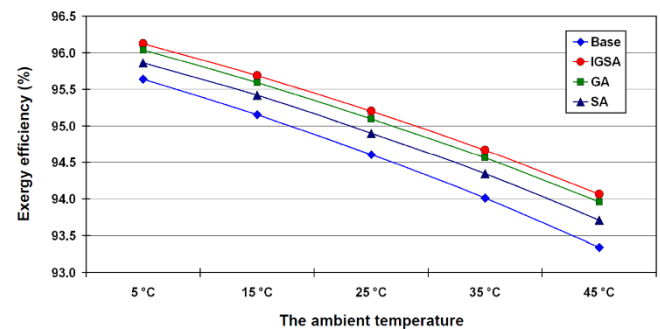


Fig. 7. Change in exergy efficiency of the whole observed high pressure heating system in four observed cases

6. Conclusions

In this paper is performed exergy analysis of high pressure feed water heating system and all of its components, which operate in nuclear power plant. The main conclusions are:

- Increase in the ambient temperature increases exergy destructions and decreases exergy efficiencies of the whole analyzed system and both of its components in all observed cases.

- From the exergy destruction aspect, target heater for optimization is HPH2, because optimization algorithms decrease its exergy destruction.
- From the exergy efficiency aspect, regardless of the observed ambient temperature, all optimization algorithms increase exergy efficiencies of the whole heating system and both of its components.
- The highest exergy efficiencies for the whole high pressure heating system and both of its components are obtained by using IGSA, regardless of the observed ambient temperature.
- In general, exergy analysis of observed system and both of its components confirm the superiority of the IGSA algorithm, but in addition, when observing exergy destructions only (for the whole analyzed system as well as for both of its components), IGSA and GA has the same trends and resulted with almost identical values.

7. Acknowledgment

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Studies on bimetallic ingots for armour by the methods of non-destructive testing

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Abstract: We have carried out researches for working out technological electrosag remelting conditions to produce bimetallic ingots. A new plant flow diagram has been developed for the manufacture. Experimental series of melting was performed on a laboratory electrosag remelting installation by developed by us electrosag remelting conditions. Bimetallic ingots for armour were produced of different combinations steel grades. Ingot of X38CrMoV 5 1 (DIN 1.2343; AISI H11)-10G2SF perspective steel grades is investigated. By the method of non-destructive testing the fusion of two steel grades along height of ingot is investigated. Macrostructure of cast transverse templates is investigated. A complete fusion of steels is established.

Keywords: ELECTROSLAG REMELTING, BIMETAL, STEELS, NON-DESTRUCTIVE TESTING, MACROSTRUCTURE

Introduction

A bimetal is a two-layer or multilayer material consisting of two different metals or alloys, fused in one monolytic whole. In the two or multilayer rolled stock the layers as a rule execute different functions and according to them are referred to as basic and cladding. The basic layer performs the role of a force component and it has greater thickness. Higher corrosion-resistance, wear resistance or electric conductivity can characterize the cladding layer depending on the requirements for a bimetal. It is also of a smaller thickness. The composite materials, to which a bimetal refers, are made by purposeful fusion of two or more components in an united material. Composite materials should satisfy the following criteria: the components of a composite are selected and fused in an uniform material consciously and purposefully; they are a result of a technological process, in their final form they are not found in nature; they contain not less than two different phases regularly distributed in the whole volume of the material; they have new useful properties superior to the properties of the available materials and their components. An essential advantage of the bimetal is its lower price in comparison with the same monometal products produced only of one cladding layer. Hence, the ratio of layers has an important meaning. Usually the thickness of the cladding layer represents 10-20 % of the total thickness, but not less than 1.5-2 mm [1, 2].

The most frequently used methods for producing bimetal are based on deformation, detonation forming, thermal diffusion, special processes of melting and electrochemical deposition. Among the known methods for obtaining bimetals the metallurgical or so-called casting methods of bonding are of interest. These are methods for fusion of the components as a result of interaction between molten and solid metal. By this method large ingots of up to 13 tons, as well as small ingots of several kilograms are produced. Methods, which are based on electrosag technologies, such as electrosag remelting (ESR), electrosag moulding (ESM), electrosag heating (ESH) and others also have found wide application for obtaining of multilayer composite materials. The method ESR provides the possibility to reinforce large size ingots, which results in practically a new class of composite materials. The manufacture of bimetallic ingots by the ESR method is broadly used in the industrially developed countries. It has achieved particular progress in Japan and Russia [3, 4]. An essential advantage of the casting method is that it may be performed in any metallurgical works, having an ESR installation and plate rolling.

The main purpose of this work is the carrying out of researches for developing optimum conditions for a new ESR technology and production of bimetallic ingots. Non-destructive investigations of the new produced bimetallic ingots for armour.

2. Experiments:

For the production of high-quality metal the exactly determined interactions between the technological remelting parameters (current, voltage, mass speed of melting etc.) and the crystallization parameters of the steel (depth and shape of the liquid metal bath, length of the two phase zone, the time during which the metal is in liquid and in liquid-solid state etc.) are of crucial importance. A

basic qualitative index, characteristic for the technological parameters and the parameters of crystallization is the coefficient of crystallization front. It is the ratio of the radius of block to the depth of conic part of the metal bath. The coefficient of crystallization front is in itself the tangent of the angle between the crystallization front incidence and the axis of the block. Experimental melts are carried out on a laboratory electrosag remelting installation (ESRP 0,125) [5] in the Institute of metal science, equipment and technologies „Akad. A. Balevski” with hydro and aerodynamics centre, Bulgarian Academy of Sciences on a cupreous crystallizer with water cooling. The „know-how”, developed by us, for production of bimetallic ingots with complete fusion of two layers is used. Ingot of X38CrMoV 5 1 (DIN 1.2343; AISI H11)-10G2SF perspective steel grades is investigated.

Non-destructive investigations are carried out in the Laboratory for non-destructive testing in IMSET with HAC-BAS. License I-1193 registration number 04328 for using of ionizing ray sources for scientific and economic purposes. Non-destructive control with radiation methods and with roentgen defectoscope of type 200/5 model MXR-200. Technical parameters: spot focus 2,45x2,80 mm; anode current 5 mA; tension 180 kV at measured equivalent dose 0,210 mSv with tapping $\pm 0,8$ %. Work conditions and reading of the roentgenograms are conformity with Standards BDS EN ISO [6, 7].

Point of the non-destructive testing: Roentgen (X-ray) or Gamma rays are using in the radiation control methods. They penetrate across optical untransparent bodies and operate over photographer's films similar to light rays. Under their operation some substances like for example Zink sulphide, shining (luminescence).

In the roentgen graphic control the radiation source (Roentgen pipe) is placing at a certain distance from object so as the rays to be direct perpendicularly on the axis. On the contrary side Roentgen film is settings. In the irradiation time (X-ray treatment) the film is situated under action of rays in the course of determinate time named exposition. Follows removal of the film in dark from the cassette, development and fixing in order to obtaining a steady photographer's picture. As a result on the section of the investigated object on separate places the picture is with irregular degree of tarnish. Rays who fall into film after passing through a defect are absorbing to a smaller degree in comparison with the rays passed through dense metal. First rays cause stronger darkening of determinate section of the film [8, 9]

3. Results

For producing bimetallic ingots a new flow diagram is developed: production of bimetallic ingots by the ESR method with a complete fusion of the two layers. Experimental series of meltings were carried out on a laboratory electrosag remelting installation in the Institute of metal science, equipment and technologies „Akad. A. Balevski” with hydro and aerodynamics centre, Bulgarian Academy of Sciences. By means of the non-destructive testing methods dense fusion of the steels is established. Difference along height of the produced ingot is not observing. Only in one of steel grade (10G2SF) defects are established, which is not typical for electrosag remelting process (Figures 1, 2, 3). Practice shows that

after rolling operation defects are not observing. Investigations continue with improving on the new plant flow diagram. Dense

macrostructure of cast transverse templates is obtained. A complete fusion of steels is established

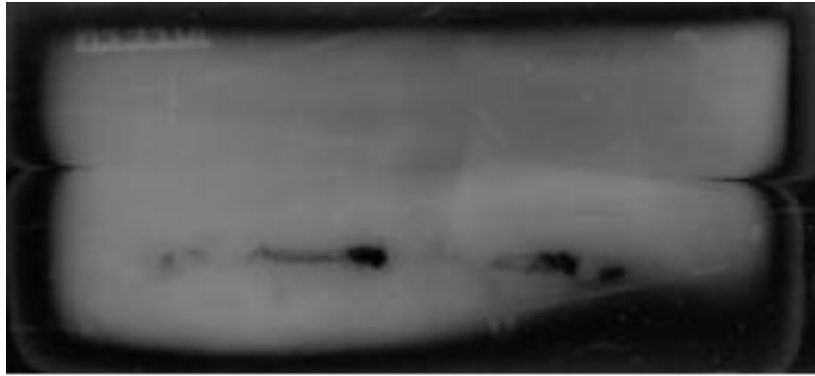


Fig. 1

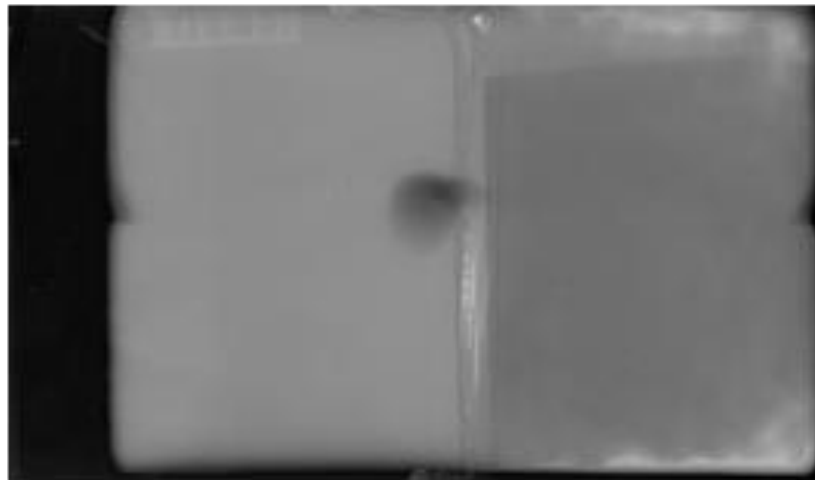


Fig. 2



Fig. 3

Fig. 1, 2, 3. Roentgen graphic images from non-destructive testing

4. Conclusions

The features of the bimetals and the trends in their production by the foundry method have been studied. The most frequently used technological variations of bimetallic ingots production have been analyzed. Research for developing optimum ESR conditions for production of bimetallic ingots has been carried out. A new plant flow diagram of manufacture is developed. On a laboratory electroslag remelting installation experimental series of meltings

have been performed. Bimetallic ingots of different steel grades have been produced. Ingot of X38CrMoV 5 1 (DIN 1.2343; AISI H11)-10G2SF perspective steel grades is investigated. By the method of non-destructive testing the fusion of two steel grades along height of ingot is investigated. The analysis of the macrostructure of the cast transverse templates from bimetallic ingot of the investigated combination of steel grades shows that the macrostructure is dense, with non-essential defects (Fig4). Complete fusion of steels is established

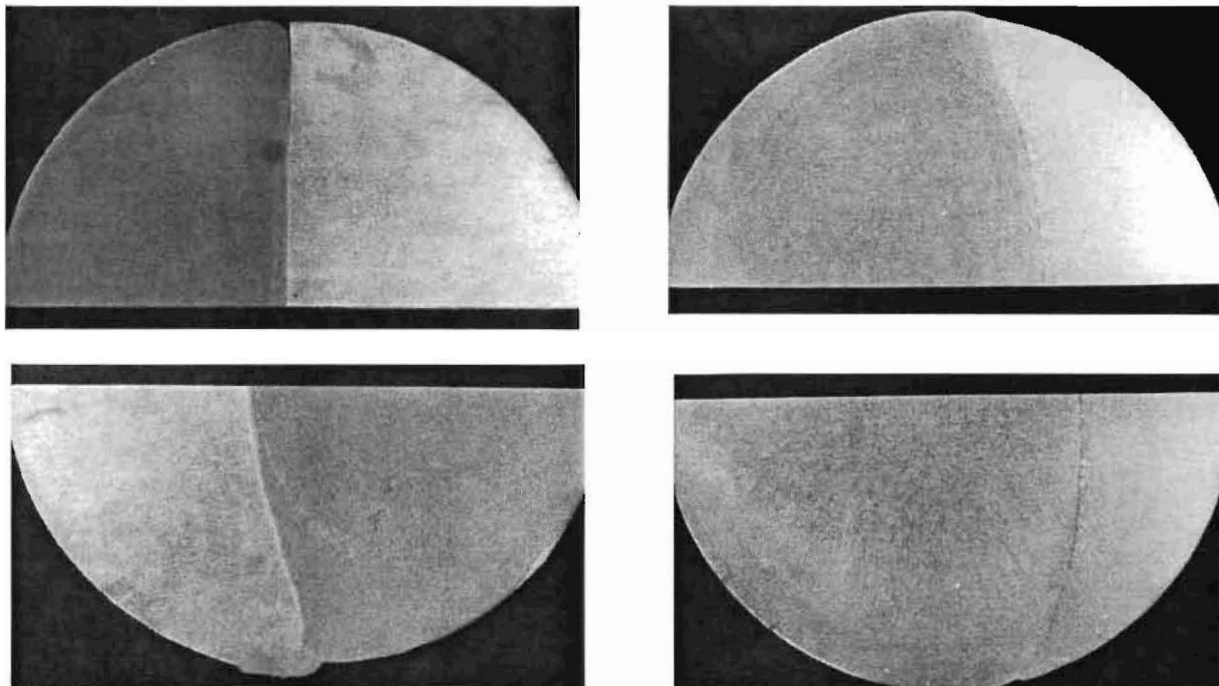


Fig.4 Macrostructure of bimetallic ingot X38CrMoV 51- 10G2SF steels.

The results can be used in the research to be carried out within the Science and Education funded project “Quantum Communication, Intelligent Security Systems and Risk Management” (Quasar), funded by the EU FUNDS for Smart Growth.

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Improving the Corrosion Resistance of Carbon Steel Cylindrical Pipe by Nano-Materials Coating, Part -1.

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Abstract: Recent research has shown that the Nano coating materials play a vital role in improving performance of corrosion resistance in hostile environment and enhancing the mechanical properties and reducing the dimension changes. Due to the superior capabilities of Nano coating in many benefits which can be achieved, in addition to corrosion resistance, mechanical properties, make it smoother, stronger and improves its adhesive properties. In this work, the effect of anti-corrosive nanomaterials (Cobalt and Zinc) coating on chemical corrosion behavior and mechanical properties of carbon steel cylindrical pipe were studied in detail. The Nano-coating was done with different thicknesses (300nm,600nm,900nm and 10 μ m), then analyzed using ANSYS software technology (version .19).The results showed that there is a strong relationship of corrosion improvement with improving mechanical properties, especially surface deformation resistance, elastic strain and stresses reduction of the inner pipe surface which contains a pressurized corrosive fluid. The maximum improvement was with the thickness of the cobalt coating (10 μ m. The result of improvement in corrosion resistance of the cobalt-coated surface is approximately (5.165%) compared to the uncoated surface, also, the results showed an improvement in mechanical resistance and corrosion resistance because of deposition of cobalt particles better than zinc particles in all different thicknesses, with a maximum of about (66%) compared to zinc. Therefore, can conclude that the improving corrosion resistance due to coating with nanomaterials is very promising.

KEYWORDS: MECHANICAL PROPERTIES, NANO, COATING, ZN, CO, AND CARBON STEEL, ANSYS-19.

List of Abbreviations: ALD: Atomic Laser Deposition, CVD: Chemical Vapor Deposition, ISO: International Organization for Standardization, MWCNT: Multi-Wall Carbon Nanotubes, SEM: Scanning Electron Micrographs, SCC: Stress Corrosion Crack, Co: Cobalt, Ni: Nickel, nm : nanometer, Zn : Zinc, μ : surface Roughness, E: Modulus of elasticity, ν : Poisson's ratio, σ : Sigma (tensile stresses), P: Fluid pressure

Background: A relationship formed between corrosion and the degradation of metals' mechanical properties. The further corrosion the metal undergoes, and both the tensile strength and fracture strength of the metal are diminished by the corrosion .Corrosive wear is also known as chemical wear or oxidation. Due to the chemical and electrochemical interaction of the surface and the environment, this form of wear can occur. In corrosive wear, the fine corrosive products on the surface reflect the wear debris. As the shaped layer is broken or removed by sliding and abrasion because of corrosion, another layer starts to form, and the process of removing a new corrosive layer formation repeated. The most common corrosive media are water, seawater, oxygen, acids, chemicals, atmospheric hydrogen sulfide and sulfur dioxide. Corrosion can have a variety of negative effects on metal. When metal structures suffer from corrosion, they become unsafe which can lead to accidents, such as collapses. Even minor corrosion requires repairs and maintenance [1]. Corrosive wear can be minimize by selecting the right materials that will resist environmental attack, by applying different coating methods. This can Control the environment, and reducing operating temperatures in order to lower the rate of chemical reaction. Researchers distinguished by being a corrosive complex medium due to the high salt content, dissolved organic substances, such as carbohydrates and amino acids, and dissolved gasses such as (chiefly nitrogen, oxygen, argon, and carbon dioxide). The presence of carbonates, chloride and other component will influence seawater chemistry significantly and lead to the formation of scale at the membranes and in piping structures. This lead to severe corrosion of alloys, especially carbon steel, and with high level of presence of dissolved oxygen, corrosion will accelerate [2], as can be seen in figure (1) shows an example of corrosion effect on bolts, valves, flanges, piping, and pipe support.

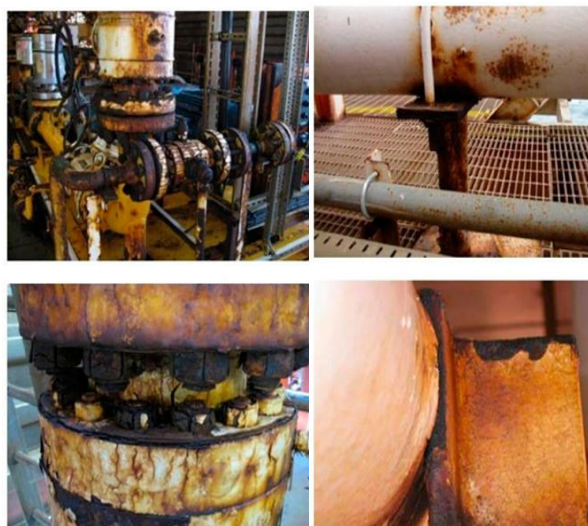


Figure (1) Example of corrosion effect on bolts, valves flanges, piping, and pipe support [2]

One of the most important problem of damage that contribute to reduce both the static and cyclic strength of a performance of thin-walled structures that immersed in seawater such as pipelines is corrosion problem. It is a process depend on a time, local environment inside or near the pipeline and occur on the internal and external surfaces in the pipe ,in the base material and contact welding. As such, protection of metal equipment in a seawater environment will give prime consideration [3].

Predicting the rate of corrosion of a steel structure in seawater is one of the difficult tasks facing design and corrosion engineers. The main parameters that effect on the rate are dissolved oxygen, salinity, temperature, ph and Sulphur [4]. Protective coatings are one of the most important methods used to reduce metal waste caused by surface corrosion, which leads to extend the life of metal equipment. Example of these coatings are chromized or aluminized coatings [5]. Chromatid zinc deposits give a better protection against corrosion compared to unprotected zinc that was corrodes quickly in chloride medium [6]. In present work a more advanced coating will be used which is a Nano-coating.

Corrosion and Nanomaterial:

The field of nanomaterial have found one of the most promising topics in different applications such as chemistry, engineering, physics, biology that will change the direction of nanotechnology advances in wide range of fields. The term "nanomaterials" employed to describe of the creation and exploitation the materials where at least one dimension in the range from approximately 1-100 nanometer. Due to their unique properties in nanoscale, observations showed that nanomaterial's are different from their bulk moieties and cannot be studied as same as from their bulk molecules [7]. The use of nanomaterials reduces the content of costly and toxic elements in alloy components, which gives high profitability in material cost, excellent performance, and enhances the mechanical properties of the coating. Electrodeposition and sol-gel chemistry method are attractive techniques in Nano-coatings applications, as it is cheaper and novel strategies [8]. Nano coatings have significant potentials to resistance the corrosion performance of surfaces compared to micro material coatings. Due to their fine grain sizes, nanocrystal line structures are superior over microstructures for corrosion resistance .where provide a better filling ,a higher integrity of the coated surface and it also called for the availability of chromium-toxic coating replacements . However, the coating thickness and composition should optimize to avoid decrease its protective characteristics towards corrosive and eroding influences [9]. Corrosion induces changes in the composition of the elements and decreases in grain size, contributing to the deterioration of corroded materials' mechanical properties (yield strength, ultimate strength, and failure strain). Applied stress accelerates corrosion and the loss of ultimate strength and failure strain of corroded materials exacerbated by its interaction with corrosion [10]. The tribo-corrosion behavior does not depend on the electrochemical environment only. There are other factors that play it's role in the corrosion process, such as design, equipment, and operating conditions, these factors do not affect independently, but depend on each other. Anti-corrosion nanomaterials and their coatings play an important role in improving mechanical properties such as ductility, high hardness, etc. in addition to surface properties such as residual stresses, surface roughness and distribution of particles on surface [11].

Research Objectives: In present study the following main objectives will achieved:

1. Study and analyze the improvement of corrosion properties when using a Nano coating for carbon steel cylindrical pipe subjected to sever corrosive environment with relationship of mechanical properties improvement.
2. Selection nanomaterials that have shown better properties for anticorrosion resistance especially in salty water.
3. Study and analyze the surface roughness before and after deposition of nanomaterials of different thickness and recommending the best one.
4. Analyze the improvement of mechanical properties of the study materials after coating by anticorrosion nanomaterials and find a relationship between these improvement and corrosion resistance.

Research Methodology:

A comprehensive review of the literature pertaining to Nano materials and their applications in the field of corrosion has undertaken in order to achieve the above objectives for this

research. Then a group of nanomaterial's with corrosion-resistant properties will be selected and simulated the effect of apply Nano coating technology using ANSYS software on a thick-walled cylindrical pipe that carries salty water under internal pressure, using electrodeposition Nano coating method. After that will study and analyze the results and compare the changes in corrosion mechanical and wear properties before and after applying coating by nanomaterials of different thickness.

The Geometric modeling of the study: One finite element model has created. Thick walled cylindrical pipe coated with different Nano thickness of Zinc and Cobalt materials separately, as in figures (2 to 5), which show the pipe specimen will analyze and coated during this work. At the beginning, the CAD geometry built using space claim in ANSYS with the given dimensions. Geometry transferred into ANSYS mechanical and thin Nano layer defined on the inner surface wall using surface coating from ANSYS.

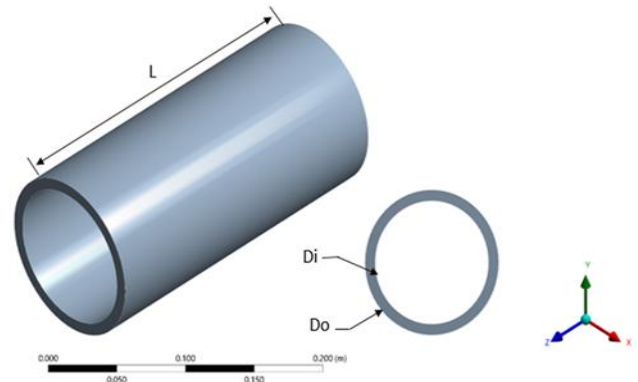


Figure (2) Front and ISO views of thick-walled cylindrical pipe specimen with dimensions.

Where: $L=0.25\text{ m}$ $Do=0.1143\text{ m}$ $Di=0.0971804\text{ m}$

Mesh Details: Parts was converted to small elements in order to use FEA methods for solving the problem, refinement of mesh was done on the inner wall where the Nano coating is located in order to get more accurate results, number of Nodes is 143620 and elements is 71929.

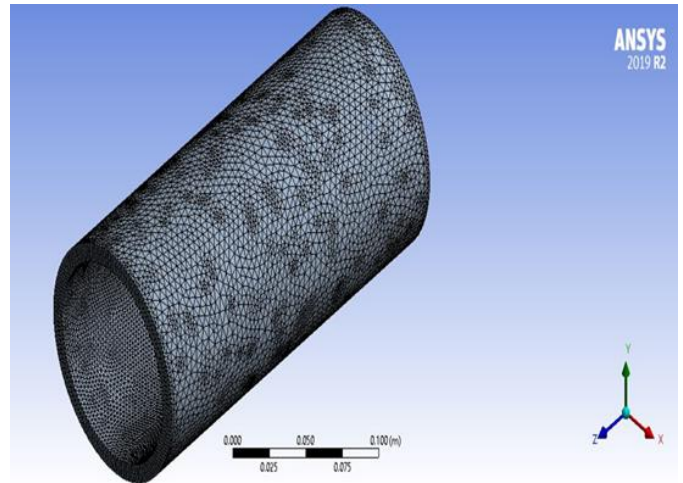


Figure (3) Thick-walled cylindrical pipe with 4.5 mm on outer and side faces and 3.5 mm on inner face elements size of mesh.

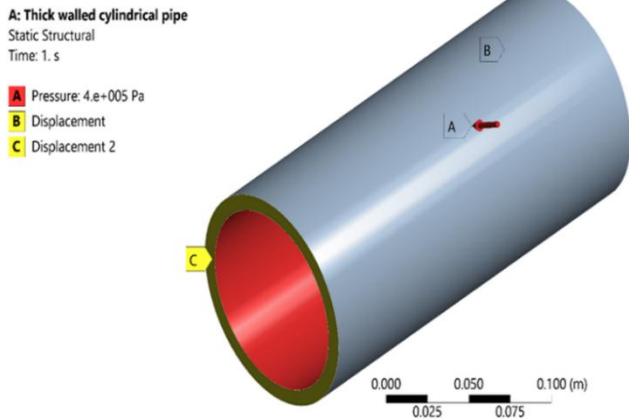


Figure (4) Boundary Condition of thick-walled cylindrical pipe specimen.

Materials:

In the present work cobalt and zinc which are anticorrosion nanomaterial's will be used to apply coating on a thick-cylindrical pipe made from carbon steel, the physical, chemical and mechanical properties of the materials will be analysis before and after coating by Nano-materials.

Carbon Steel:

Carbon steels defined as those containing iron, carbon, and manganese. There are three type of carbon steel depend on the amount of carbon content is low carbon, medium carbon, and high carbon steel which contains 0.6–1.4% carbon [14]. It is the most widely used engineering material for service in seawater and many engineering applications in high temperature conditions such as power plant, chemical treatment, mining, mineral equipment Processing and other industrial fields, it offers many advantages of low price, easy availability, ease of fabrication, and a satisfactory rate of corrosion [15]. Carbon steel piping and tubing because of their minimal resistance to corrosion there are limits on their operating time [16].

Zinc:

Zinc is the fourth most used engineering metal in the world, a bluish-white metal, and one of the main uses for zinc is steel coating to protect against corrosion in the presence of an electrolyte such as moist soils or seawater.

Cobalt: Cobalt is one of the rare elements in the Earth's crust of about 0.100%, usually distributed in conjunction with nickel, lead, silver, iron, etc. It is a white, hard-bluish, ferromagnetic metal, relatively unreactive and slowly dissolves in mineral acids without union with hydrogen or nitrogen [12]. Cobalt is now widely used in the production of alloy steel, which is the base metal in most of them. Cobalt alloys distinguished by being strength, high melting point, and high resistance to oxidation [13].

Results and discussions: Mechanical properties including the principle stresses, deformations, linear stress resistance and the consequence on corrosion resistance were studied for carbon steel [ASTM A53 (ASME SA53)] thick walled cylindrical pipe, the pipe is coated with different Nano thicknesses of Cobalt (Co) and Zinc (Zn) with different thicknesses. The study was conducted and running through surface coating technique using ANSYS Software, Product Release 19.2. Uniformly distributed pressure (4 bars) applied on the inner walls of the pipe this is the same. Initially the boundary conditions were applied before coating the pipe and then the same conditions applied after the pipe coated by Cobalt or Zinc at different thicknesses (300nm, 600nm, 900nm and 10 μ m), then the mechanical properties on the pipe were measured.

a) Total Deformation: Deformation in X,Y, and Z directions was measured using total deformation resulted due to applying uniformly distributed internal pressure, figures (14) and table (1) show the values of the total deformation before and after

coating thick-walled cylindrical pipe with different Nano thicknesses of Cobalt and Zinc separately.

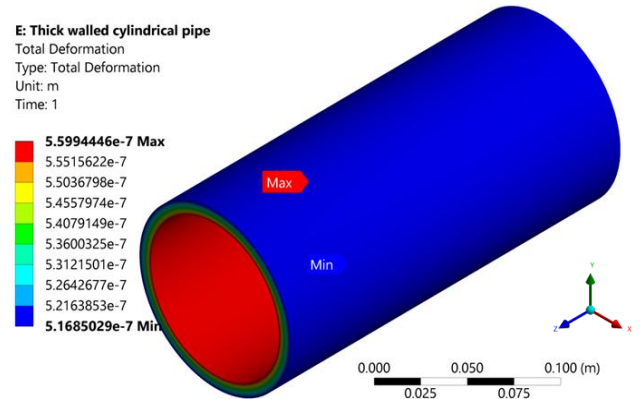


Figure (5) Total Deformation of Carbon steel (ASTM A53) without coating.

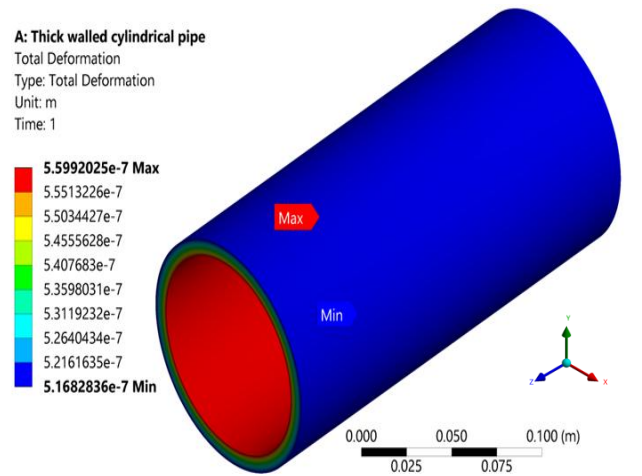


Figure (6) Total Deformation of Carbon steel (ASTM A53) with 300 Nanometers of Cobalt.

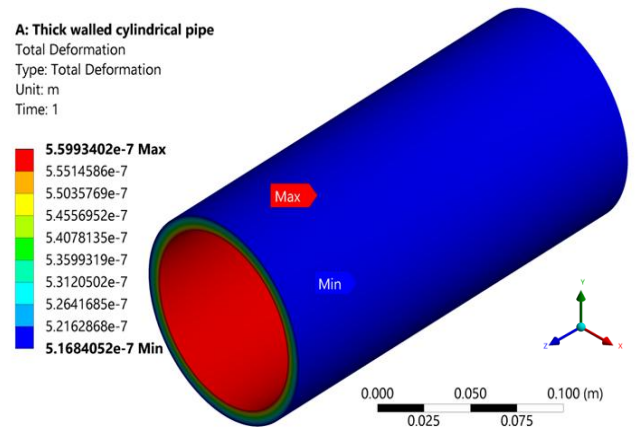


Figure (7) Total Deformation of Carbon steel (ASTM A53) with 300 Nanometers of Zinc.

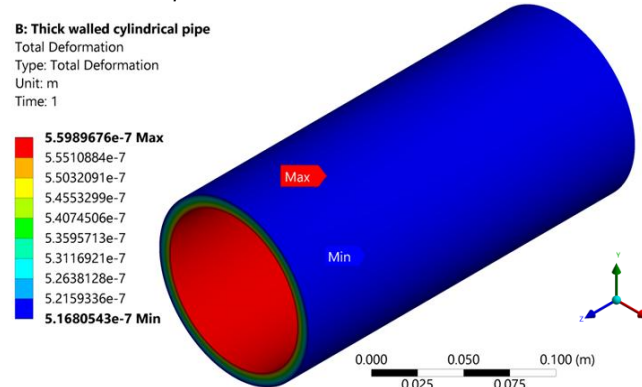


Figure (8) Total Deformation of Carbon steel (ASTM A53) with 600 Nanometers of Cobalt.

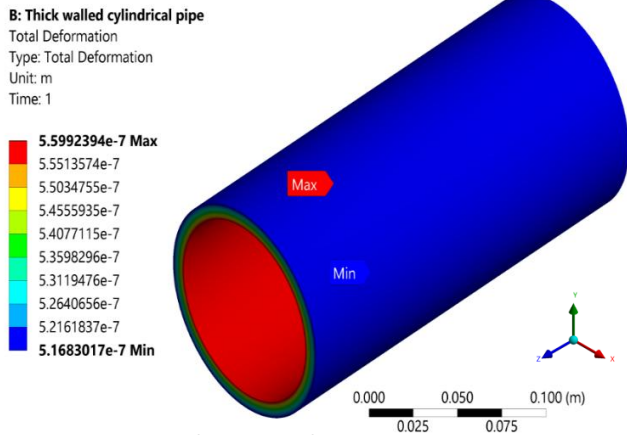


Figure (9) Total Deformation of Carbon steel (ASTM A53) with 600 Nanometers of Zinc.

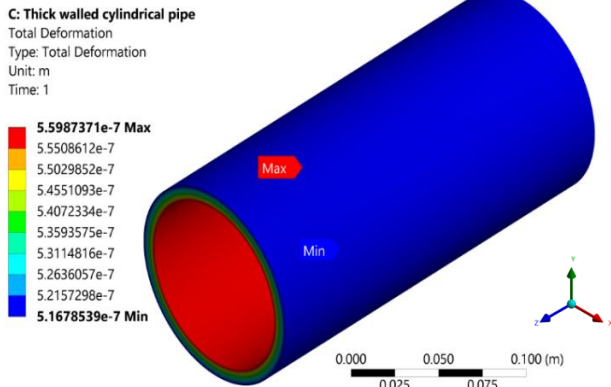


Figure (10) Total Deformation of Carbon steel (ASTM A53) with 900 Nanometers of Cobalt.

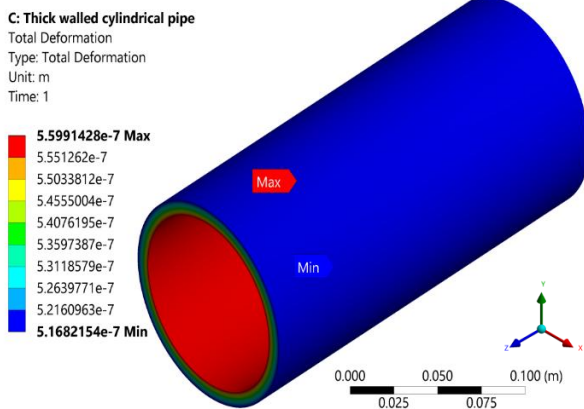


Figure (11) Total Deformation of Carbon steel (ASTM A53) with 900 Nanometers of Zinc.

Table (1) Percentage change in maximum values of total deformation (Δ) and corrosion resistance at different thicknesses.

Coating Thickness	Cobalt (Co)			Zinc (Zn)		
	Absolute Value of Δ (m)	improvement %	Corrosion Resistance %	Absolute Value of Δ (m)	improvement %	Corrosion Resistance %
0.0 nm	5.5994446E-07	0	0	5.5994446E-07	0	0
300 nm	5.5992025E-07	0.004323643	0.658	5.5993402E-07	0.001864471	0.432
600 nm	5.5989676E-07	0.008518702	0.923	5.5992394E-07	0.003664649	0.605
900 nm	5.5987371E-07	0.012635182	1.124	5.5991428E-07	0.00538982	0.734
10 μ m	5.5916712E-07	0.138824483	3.726	5.5960190E-07	0.061177496	2.473

Improvement percentage = $\frac{(\text{original value} - \text{new value})}{(\text{original value})} \times 100\%$ Original value: value before coating. New value: value after coating.

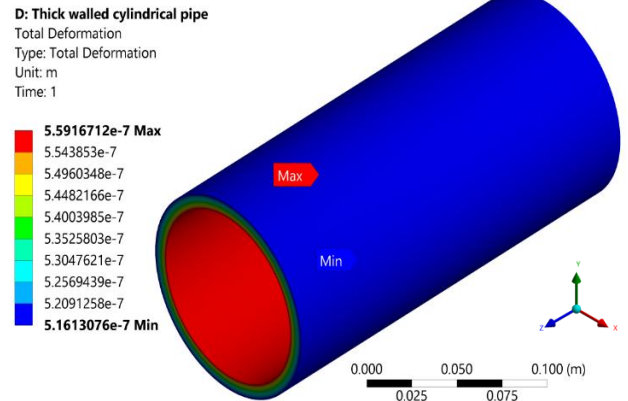


Figure (12) Total Deformation of Carbon steel (ASTM A53) with 10 Microns of Cobalt.

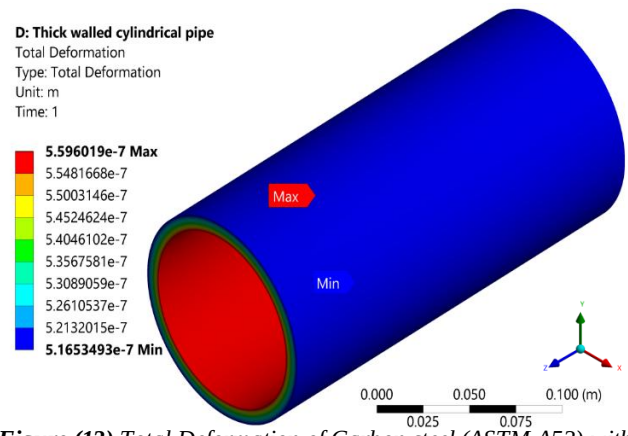


Figure (13) Total Deformation of Carbon steel (ASTM A53) with 10 Microns of Zinc.

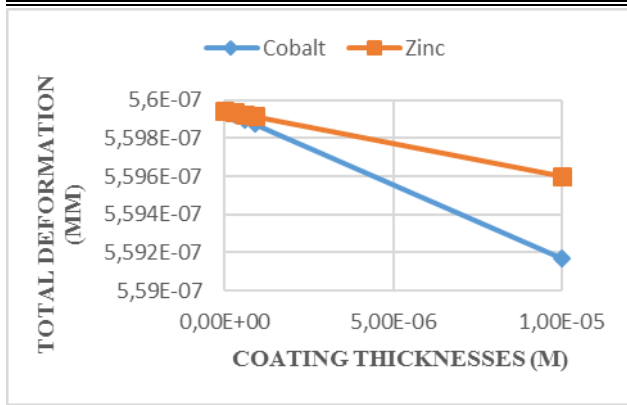


Figure (14) Comparison of maximum total deformation values (mm) at different thicknesses (m) for Cobalt and Zinc

b) Normal Elastic Strain: Normal elastic strain is the line segment elongation or contraction resulted from normal stress perpendicular to the face of an element and is equal to change on length over the original length.

1, Normal Elastic Strain ϵ_L (longitudinal Strain)

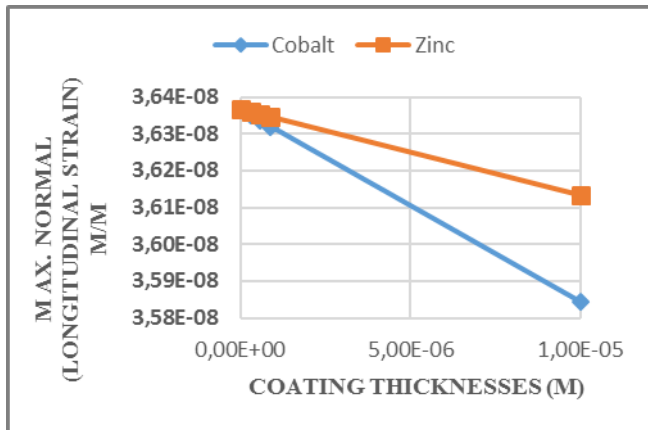


Figure (15) Comparison of maximum normal elastic strain (Z-axis) values at different thicknesses (m) for Cobalt and Zinc.

2. Normal Elastic Strain (hoop strain)

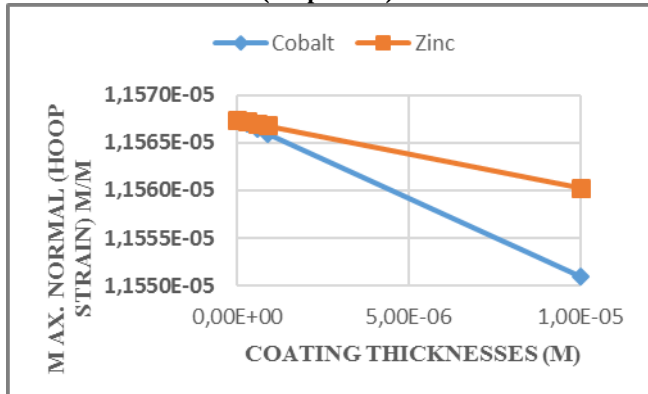


Figure (16) Comparison of maximum normal elastic strain (X-axis) values at different thicknesses (m) for Cobalt and Zinc.

c) Normal Stress σ : A normal stress occurs when a part loaded by an axial force and hence tension or compression stresses are resulted. The value of the normal force represent by force divided by the cross sectional area.

d) Equivalent Stress σ_e :

Equivalent stress (Von misses stress) usually utilized in design because it is able to represent any three-dimensional stress state as a single positive stress value Equivalent Stress represented as results of applying uniformly distributed internal pressure, figure (19) and table (2) show the values of improvement equivalent stress after coating with different Nano thicknesses of cobalt and zinc separately. It can notice that maximum value of stresses are located at the inner surface of the pipe and it is gradually decrease through thickness to outer surface, which have minimum values of stresses.

1-Normal Stress σ_L (longitudinal stress): Normal stress (Z-axis) direction is represented as results from applying uniformly distributed internal pressure along the longitudinal axis; figures (15-18) show the values of normal stress (Z-axis) after coating with different Nano thicknesses of Cobalt and Zinc separately on thick-walled cylindrical pipe.

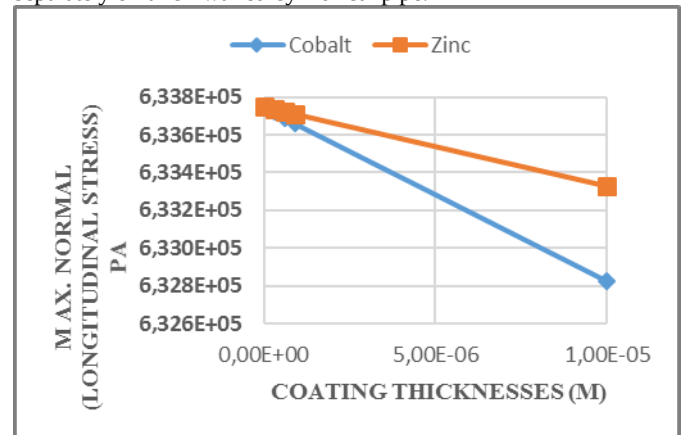


Figure (17) Comparison of maximum normal stress σ_L (Z-axis) values at different thicknesses (m) for Cobalt and Zinc.

2. Normal Stress σ_h (hoop stress)

Hoop stress is the stress on a cylindrical pipe wall that works in a plane perpendicular to the pipe's longitudinal axis. Normal stress (X-axis) direction represented as results of applying uniformly distributed internal pressure; figure (15-17) and table (2) show the values of normal stress (X-axis) that improved after coatings.

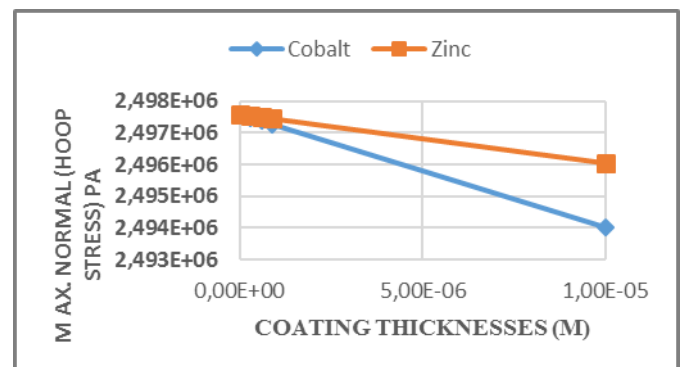


Figure (18) Comparison of maximum normal σ_h stress (X-axis) values at different thicknesses (m) for Cobalt and Zinc.

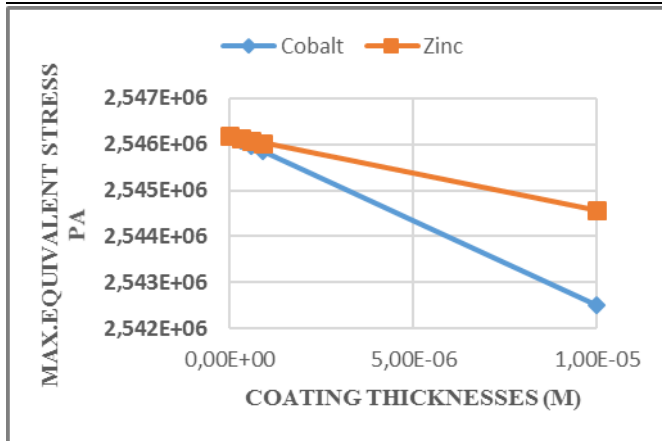


Figure (19) Comparison of maximum equivalent stress σ_e values at different thicknesses (m) for Cobalt and Zinc.

e) Shear Stress τ :

Shear stress is the stress caused by two equal and opposite forces in a body, which work tangentially across the resistant portion [17].

1. Shear Stress in XY plane: Shear stress in XY plane is represented as a results of applying uniformly distributed internal pressure, figure (20) and table (2) show the values of maximum

shear stress (XY plane) after coating with different Nano thicknesses of cobalt and zinc separately.

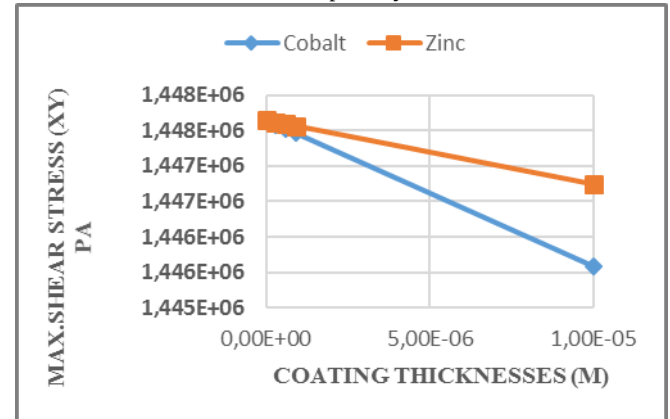


Figure (20) Comparison of maximum shear stress (XY plane) values at different thicknesses (m) for Cobalt and Zinc.

Table (2) Summary of improvement percentage with different coating thicknesses and materials

	Improvement of Cobalt (Co) %				Improvement of Zinc (Zn) %			
Coating thickness	300 nm	600 nm	900 nm	10 μ m	300 nm	600 nm	900 nm	10 μ m
Total deformation	0.0043	0.0085	0.0126	0.1388	0.0018	0.0036	0.0053	0.0611
Normal Elastic Strain X axis	0.0042	0.0085	0.0128	0.1423	0.0018	0.0037	0.0056	0.0623
Normal Elastic Strain Z axis	0.0436	0.0872	0.1307	1.4330	0.0192	0.0384	0.0576	0.6367
Normal Stress X axis	0.0048	0.0096	0.0144	0.1453	0.0021	0.0042	0.0063	0.0663
Normal Stress Z axis	0.0042	0.0085	0.0128	0.1424	0.0018	0.0037	0.0056	0.0624
Equivalent Stress	0.0041	0.0085	0.0128	0.1431	0.0018	0.0037	0.0056	0.0627
Shear Stress XY plane	0.0042	0.0085	0.0128	0.1423	0.0018	0.0037	0.0056	0.0623
Shear Stress XZ plane	0.0224	0.0439	0.0655	0.7148	0.0103	0.0197	0.0292	0.3158
Average Corrosion Resistance	0.846	1.255	1.548	5.165	0.558	0.786	0.959	3.406

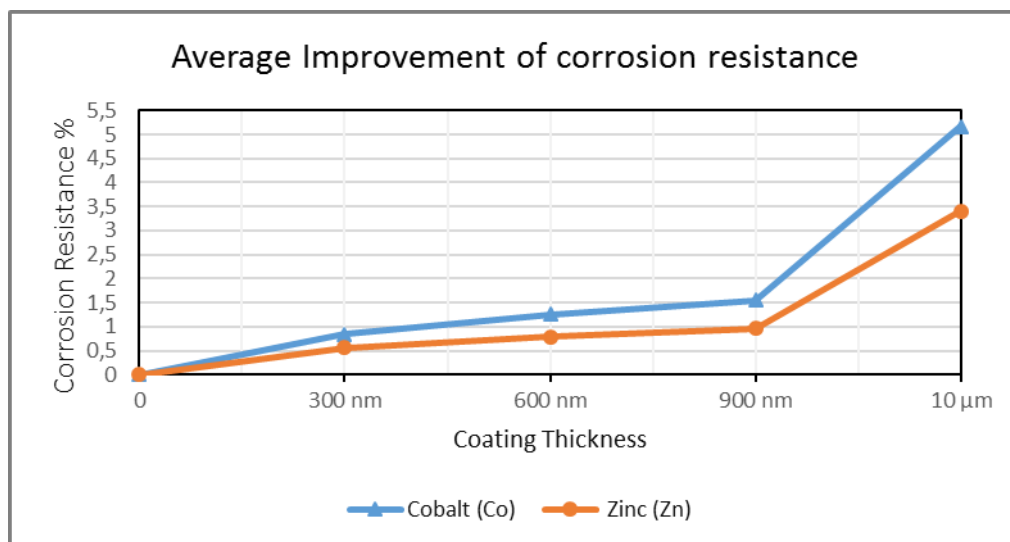


Figure (21) Average Corrosion Resistance Improvement with different Nano coating thicknesses of cobalt and zinc.

Table (2) shows a summary of improvement percentage of all deformations and stresses results with different coating thicknesses and coating materials, in addition to the rates of improvement in corrosion resistance is tabulated too. The maximum value of improvement in mechanical properties for all the studied cases is about 0.71% when coated with 10 μ m of Nano Cobalt material, while, the improvement in corrosion

resistance is about 5.2% . In other hand, the corresponding improvement for Zinc coating is 0.31% and for corrosion is 3.4%. In addition, the results showed that for the normal elastic Strain Z-axis and shear stress-XZ plane with the values of 1.4330 % and 0.7148 % respectively, when using cobalt coating. The rate of corrosion resistance, the maximum value was (5.165%) of cobalt as shown in the above figure (21).

Conclusions:

From the analysis of the above results discussion, the following main points can be concluded:

- The Carbon steel (ASTM A53) thick walled cylindrical pipe was successfully coated theoretically with anticorrosion Nano particles of Cobalt and Zinc using ANSYS software (version .19 with different Nano thicknesses of 300nm, 600nm, 900nm and 10 μm separately.
- The highest improvement in resistance of deformation is (0.1388 %) and corrosion resistance is (3.726%) when coated with 10 μm of cobalt, while the minimum improvement is (0.0018 %) when coated with 300 nm of zinc. In addition, cobalt found to improve the deformation resistance by (44.0 %) and corrosion resistance by (66.3%) more than zinc.
- The maximum improvement in resistance for both longitudinal strain and hoop strain was (1.433%) and (0.1423%) respectively when coated with 10 μm of cobalt. While the lowest value is (0.0018%) at 300 nm of zinc, that made cobalt outperform with zinc by a percentage of improvement (44.4%). Which accompanied by an improvement in the corrosion property by (11.971%), while zinc gave a good rate of improvement (7.979%).
- In both normal stresses (longitudinal stress and hoop stress) 10 μm of cobalt gave better improvement than zinc with values (0.1453%) and (0.1424%) respectively.
- Comparing to all other coatings thicknesses, 10 μm of cobalt has the highest percentage of change in reducing the equivalent stress (0.1535%).
- In shear stress 10 μm of cobalt make a highest percentage of improvement in decreasing both shear stress in (XY plane) and (XZ plane) with values (0.1423%) and (0.7149%) respectively compared to all other coatings, with rate of resistance to corrosion of (8.455%).
- The thick-walled cobalt-coated cylindrical pipe showed the largest percentage of improvement about (66 %) more in comparison with Zinc at 10 μm thickness of coating.
- Cobalt and zinc are anti-corrosion Nano materials can help to protect and improve corrosive wear resistance, as well as rising a surface's thickness. So, the Nano-coating will be a promising solution to corrosion problems.

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Technologies for joining dissimilar materials in the automotive industry

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Abstract: The paper presents the results of research aimed at determining the quality of welds in steel and aluminum alloys. Laser welding technology, fusion-pressure welding in combination with adhesive bonding were used for joining. The present research describes a new bonding technology based on the resistance welding process with a combination of adhesive bonding. Its implementation allows the joining of aluminum and steel sheets at extremely short welding times with a high concentration of energy in combination with adhesive bonding. The quality of the joints was determined on the basis of the tensile shear test according to ISO 12996.

Keywords: ALUMINIUM ALLOY, SPOT WELDING, BONDING TECHNOLOGY, SHEET METAL

1. Introduction

Resistance spot welding is considered to be one of the most important joining methods in the construction of car bodies with a high proportion of steel in the automotive industry. This process is characterized by a high degree of automation [1]. To meet very strict requirements for greenhouse gas emissions, car manufacturers are working to reduce the weight of vehicles [2]. One of the many ways to achieve weight reduction is to create bodies that will be characterized by different types of materials. This combination guarantees the strength and cost savings of steel with lightweight materials such as aluminum alloys. By using the right combination of materials, engineers can optimize the weight and cost of the body structure [3,5].

Bonding different types of metals is difficult due to significant differences in their thermal and mechanical properties [6]. The main

reasons for the problems arising when joining different metals are different thermal, adhesive and mechanical properties [7]. Mechanical methods physically hold two or more layers of different pieces of material together by flow drilling screws, self-loading riveting, nailing, riveting, or winding of threaded fasteners. Adhesive bonding is a process in which several components are bonded together using a chemical adhesive. Thermal joints use heat to melt the workpiece or interlayer to create a metallurgical bond between the parts. Common methods of heat sealing parts include resistance and friction welding, brazing, plasma sintering, high energy beam welding, electric arc welding. Appropriate technological selection of joining different metals improves work efficiency, reduces material deformation, minimizes differences in thermal expansion and reduces production costs [8,11].

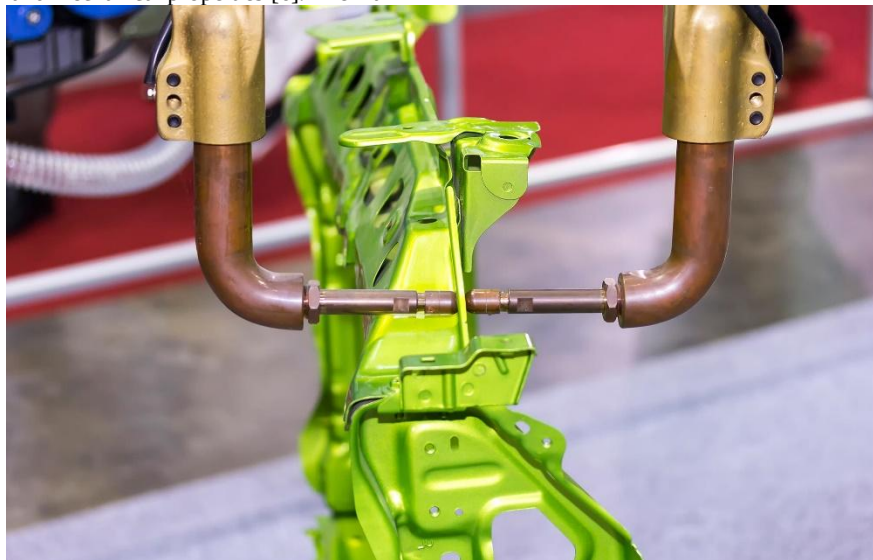


Fig. 1 Example of resistance spot welding of aluminium sheet

Resistance spot welding stands out among the various joining methods due to its high efficiency, low cost, robustness, flexibility and widespread use in similar joining of metals in automated production. Creating a high-quality resistance spot weld from Al-steel requires overcoming various obstacles. Oxides formed on the surface of the aluminum alloy can increase the contact resistance between the aluminum sheet and the welding electrode and thus limit the efficient heating of the faying interface [12,14]. If it is possible to overcome the effect of oxides on the Al-electrode interface, the melting points of aluminum alloy and steel are so different that only aluminum alloy melts during welding, while steel remains solid (melting point of pure aluminum is 660 ° C, while pure iron is 1535 ° C. Liquid aluminum wets the solid surface of the steel and forms a layer of intermetallic mixture at the interface, while the two materials bond together. IMC at the interface deteriorates the strength of the joints because IMC is hard and brittle. have a thin intermetallic composite layer, limited shrinkage

and a parallel grain size of less than 500 nm [15] Another problem with Al spot resistance welding on steel is electrode wear. During Al spot resistance welding, the heat generated by the current flow can cause a reaction between the Al sheet and This reaction causes Al to adhere to the copper electrode, reducing the life of the electrode [16].

Arghavani et al. joined aluminum alloy 5054 with galvanized steel by resistance spot welding [17]. The thickness of the aluminum alloy was 2 mm and the steel sheet 1 mm. Welds were made with an IMC thickness of less than 5.5 µm. This paper focused more on the morphology and type of IMC layer than on the mechanical properties. Needle-shaped FeAl₃ was observed in the vicinity of the Al sheet and tooth-shaped Fe₂Al₅ was observed in the vicinity of the steel sheet.

Wan et al. they also evaluated the morphology of the IMC layer at the interface of resistance spot welds of Al-steel [18]. Two types

of intermetallic compound structures were observed, dental Fe₂Al₅ adjacent to the steel sheet and needle FeAl₃ adjacent to the aluminum sheet. Dental Fe₂Al₅ was a perfect channel for crack propagation, therefore the growth of Fe₂Al₅ was considered detrimental to the mechanical properties of the joint [19,20]. During welding, which takes a long time, the researchers observed a bimodal distribution of IMC thickness, in which the IMC was thinner in the middle of the interface and slightly thicker at the edge. However, no such phenomenon was observed when the welding time was short. It is believed that the strong cooling effect in the center of the welding electrodes limited the growth of the IMC in the middle of the interface and caused a bimodal distribution of the IMC thickness.

Although there is a literature related to resistance spot welding of Al-steel, few provide a thorough assessment of the Al-steel spot welding process against factors common in automotive manufacturing. Factors that affect this welding process are poor fit between the sheets, bad angles between the workpieces and the welding electrodes, the length of the welding electrode and small changes in current. When creating a weld, a misalignment between the two components can occur due to problems that occur during the forming, bending or pre-joining process. Improper alignment may occur between the bonded material and the electrodes, sometimes due to insufficient access or welding of the gun shanks used in the robot cell. Although each weld controller is programmed for welding currents, there may be minor differences between the welding guns, which may affect the current output to the workpiece. Because the worn electrodes are shaped by tip dressing tools, material is removed from the electrode, shortening the electrode length and increasing cooling efficiency. It is necessary to understand the influence of production variables on the process of resistance spot welding of Al-steel and the resulting properties of these joints, so that we can develop more efficient and stable welding technologies for automotive production.

2. Materials and methods

Materials were used for the formation of joints - tensile steel DC04 (EN 10130/06) without surface treatment and aluminum alloy EN AW -6082 T6 (AlMgSi0.5 F22). The chemical composition and mechanical properties of the materials are given in Table 1. The thickness of the steel sheets was 0.8 mm and of the aluminum alloy sheet 1 mm. The dimensions of the test specimens were 40x110 mm, overlap 30 mm.

Table 1. Chemical and mechanical properties of evaluated materials

Chemical composition % of steel DC 04 (1.0338): EN 10130-2006			
C	MN	P	S
Max 0.08	Max 0.4	Max 0.03	Max 0.03
Mechanical properties of steel DC 04 (1.0338)			
Tensile strength (MPa)	Minimum yield strength (MPa)	Min. elongation L ₀ =80 mm (%)	Vickers hardness (HV)
270-350	210-220	37-38	95

The steel samples were degreased with strongly alkaline, medium emulsifying degreasing agent, used for degreasing steels and cast irons by immersion and spraying. Its use consists mainly in the removal of heavy deposits of preservatives and grease from the surface of steel objects. It is unsuitable for degreasing non-ferrous metals or objects made of light metal alloys, due to their uniform etching of the surface. For this reason, it was only used for degreasing steel samples. Acetone was used to degrease the aluminum alloy. After improving the degreasing of all contact surfaces, adhesion promoter based on organosilanes was used to

improve the adhesion of the adhesives. It is a clear aqueous solution whose silica particles condense on the surface of metals or conversion layers to form a gel, colorless, transparent layer on the surface. The composition of the layer consists of epoxy functional groups, which are involved in the organic binder of the paint and thus play a significant role in increasing the adhesion of paints as well as the corrosion resistance of the paint system. Increases adhesion on degreased metal surfaces. A solution of 100 ml / l in distilled water at ambient temperature was used, immersion for 10 min, then the samples were dried. The thickness of the protective layer was 20 nm. After the surface treatment of the samples, the joints were made using spot resistance welding in combination with gluing.

A hybrid adhesive and non-adhesive welding process was used for gluing. The hybrid process is based on a two-stage projection of spot resistance welding using a connecting element and the application of glue (Fig. 1).

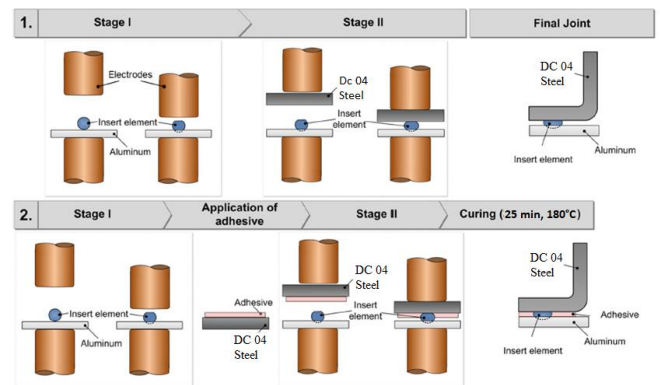


Fig. 2 Hybrid projection welding process with an insert element without (1.) and with adhesive bonding (2.) with two main stages I- securing of element on aluminium sheet; stage II- manufacturing of final joint.

The connecting element was made of stainless steel welding wire MIG 308 L Si / TIG 308 L Si with a diameter of 1.60 mm and a length of 10 mm, which enabled their cost-effective production and modification of the geometry. The advantage of using a connecting element is that an element with a relatively small contact area is created. The small contact area allows welding with short welding times and, as a result, very little total heat input. This is beneficial in the case of a hybrid bonding process in which the adhesive is not thermally damaged as in conventional resistance welding. The welding electrodes were selected on the basis of the standard ON 42 3039.71 from a Cu-Cr alloy with a diameter of $\varnothing = 5$ mm. A BPK 20 pneumatic spot welder was used [21].

The following technologies were used to create the connections:

1. Spot resistance welding with connecting element
2. Spot resistance welding with fastener and adhesive TEROSON RB 5197 (based on rubbers)
3. Spot resistance welding with fastener and adhesive TEROSON EP 5090 (based on toughened Epoxy resins)

Table 2. Welding parameters for stage I and II.

	Stage I.	Stage II.
Electrode force, F [kN]	2	4
Welding time, t [ms]	10	16
Welding current, I [kA]	8	12

The Tensile shear test (TST) was used to determine the load-bearing capacity of the formed joints. The test was carried out according to the standard ISO 14329 - Tensile test of spot and

welded weld surfaces. There were 5 connections for each combination.

3. Results

The implemented experimental work pointed out the great importance of the creation of hybrid connections. In the case of joints made without glue, the connecting element was melted after the tensile test. After the destruction of the joint, more of its volume always remained on the Al substrate, only in one case it remained on the DC substrate. Around the spot weld on the Al substrate, the extrusion of Al from the weld spot is evident, Fig.4. The maximum achieved load capacity of the joint was 1.8 kN Fig.3. No plastic deformation of the substrates was observed.

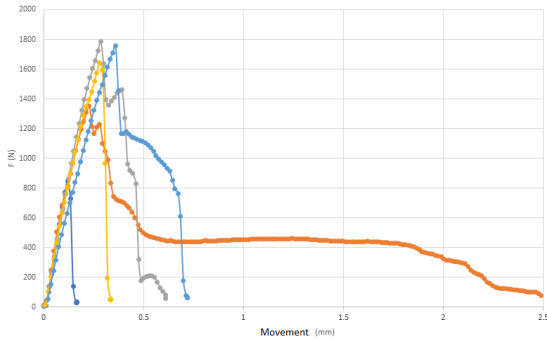


Fig. 3 Tensile shear load of joints with insert element without additional adhesive layer



Fig. 4 Appearance of the contact surfaces with the connecting element after the tensile test

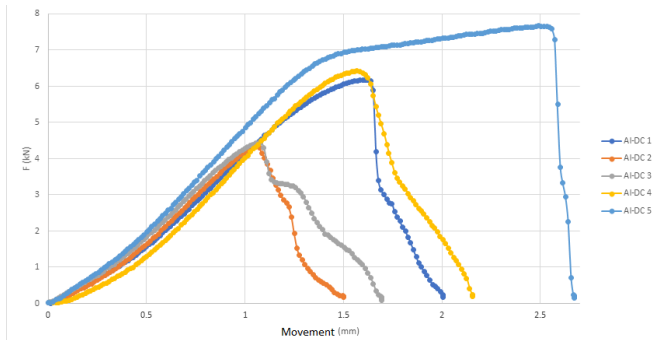


Fig. 5 Tensile shear load of joints with insert element with additional adhesive layer TEROSON RB 5197

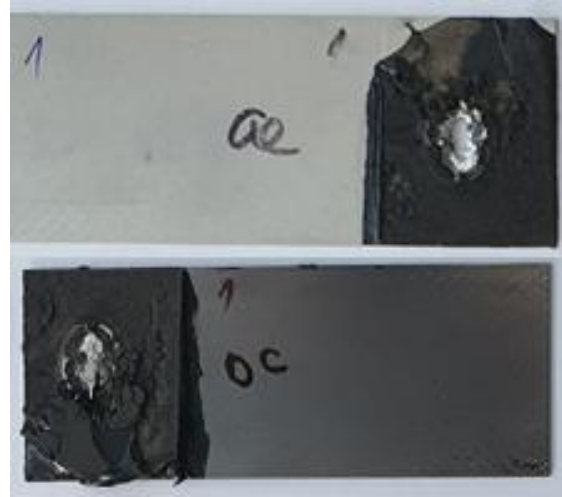


Fig. 6 Appearance of contact surfaces with connecting element and with additional adhesive layer TEROSON RB 5197

No plastic deformation of the substrates is macroscopically visible on the test specimens after the tensile test. The connecting element always remained on the DC substrate after the connection was destroyed. Glue failure was 100% cohesive in all samples, in several samples the glue was not applied in sufficient thickness, so there are smaller unconnected parts of the surface. Each Al substrate is perforated after the destruction of the joint - the connecting element and a part of the Al material were torn from the Al substrate and remained welded on the DC substrate. The maximum achieved load capacity of the joint was 7.6 kN Fig.5.

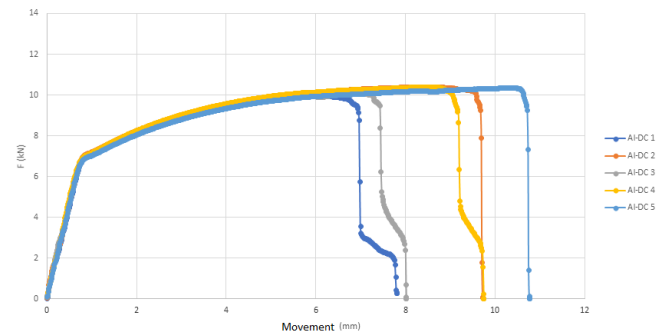


Fig. 7 Tensile shear load of joints with insert element with additional adhesive layer TEROSON EP 5090



Fig. 8 Appearance of contact surfaces with connecting element and with additional adhesive layer TEROSON EP 5090

After the test for monitoring the contact surfaces, the connecting element was always on the DC substrate after the connection was destroyed. Macroscopically visible plastic deformation of the DC substrate occurred at all joints. Adhesive

failure was mixed in all samples by adhesive-cohesive, with an adhesive fracture predominating on 80% of the joint area. The glue separated from the DC substrate, the glue remained on the Al substrate, Fig.8. For some joints, there are smaller unconnected parts of the surface. Each Al substrate was perforated after the joint was destroyed - the connecting element and a part of the Al material were torn from the Al substrate and remained welded on the DC substrate. The maximum achieved load capacity of the joint was 10.6 kN Fig.7. By using this type of adhesive, the load-bearing capacity of the joints has increased almost 6 times compared to joints formed using only the connecting element.

4. Conclusion

The article presents a new procedure of joining unequal materials. The procedure of creating hybrid joints using a connecting element and two types of adhesives was verified. A two-stage splicing process was carried out - in the first step, the splicing element was welded using spot resistance splicing technology, and in the second step, the weld itself was implemented in combination with the adhesive. Experimentally obtained results have shown that the use of this technology provides a precondition for the creation of high-quality hybrid connections. Higher load-bearing capacity of joints was achieved when using adhesives. Of the two adhesives evaluated, the forest had strength properties and provided higher bond strength to TEROSON EP 5090 (based on toughened Epoxy resins). High process stability, low thermal impact of the material and good industrial applicability provide a precondition for commercial use of this new technology. The investigated joining process and the possibility of producing simple elements with commercially available welding wires represent the potential for joining a wide variety of materials.

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Influence of external mechanical loads on change of electrophysical characteristics of film sensor elements

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Abstract: The materials of the article consider the influence of external mechanical loads of static and dynamic action (pressure force, mechanical impulse, vibration) on the change of electrophysical characteristics (electrical conductivity, specific capacitance) of film sensor elements. It is shown that an increase in the mechanical load on such an element with a simultaneous decrease in the interaction time with a constant contact area leads to an exponential increase in the power and sensitivity of the reaction pulse, provided that such mechanical load does not exceed the mechanical strength of the sensor element. At the same time, the increase in the mechanical load on the sensor element at constant time and contact area, almost does not change the sensitivity of the reaction pulse (the maximum increase in sensitivity does not exceed 1.8%). In this case, vibrational oscillations in the frequency range 30... 85 Hz at mechanical forces of the order of 20 ... 150 mN create response pulses of the order of 12 ... 45 mV/μs, which are perceived as "false positives" of the sensor elements. A further increase in frequency and mechanical effort leads to the destruction of the base of the sensor element and the detachment of the sensor film from the base. Reducing the frequency and mechanical forces create reaction pulses up to 12 mV/μs, which does not exceed the allowable values of "white noise" (about 25... 35% of the minimum value of the reaction pulse).

Keywords: FILM SENSOR ELEMENT, ELECTROPHYSICAL CHARACTERISTICS, MECHANICAL LOADS, VIBRATION, ELECTRICAL CONDUCTIVITY, SPECIFIC CAPACITANCE

1. Introduction

Today in the electronics market there is a sharp increase in the number of products and their components containing sensory contact elements. This growth is primarily due to the continuous growth of products in the field of communications and entertainment, such as: mobile phones, tablets (and more recently stationary) PCs, game consoles, controls and settings for appliances, cars, multimedia devices and others [1]. This popularity and proliferation of devices with sensor elements leads to a gradual expansion of their areas of application, both in normal conditions (domestic use) and in extreme and/or emergency conditions of extreme pressures, temperatures, and especially power dynamic loads.

Thus, a number of leading domestic and foreign scientists deal with the development and research of sensory elements of electronic devices (E.Johnson, S.Hearst, B.Boy, W.Westerman, J.Elias, E.Wilson, J.Hahn, M.Krueger, T.Kuchmenko, A.Yurin, A.Dmitriev, V.Bochenkov, V.Zagorsky) [2-4] and large firms and research and production associations (HP, Bell Labs, IBM, BellSouth, Apple, Palm Inc., DSI Datotech, Samsung, Microsoft, ARIES, CitySensors) [5, 6].

However, the important issue of studying the electrophysical characteristics of film sensor elements of electronic devices in order to determine the impact of negative negative mechanical loads on them remains unresolved.

The aim of the work: to study the effect of external mechanical loads on the change of electrophysical characteristics of film sensor elements, which increases the accuracy, reliability and sensitivity of electronic devices, as well as to expand the range of performance of these devices in normal and extreme environmental conditions.

2. Basic requirements for sensor elements of electronic devices

The main type of materials used in the manufacture of capacitive layers are thin-film semiconductor materials [7]. Such film-forming semiconductors include systems of compounds connected by double or triple bonds (polyimides, polybenzimidazoles, polybenzoxazoles and others), as well as polymer complexes with charge transfer (halogenated polystyrene, poly-α-methylstyrene, etc.). The elements obtained from these materials have increased values of electrical and photoconductivity: 10^3 - 10^9 cm/m. In this case, the best coatings have high adhesion to the substrate and low values of water absorption and electrical

conductivity (10^{16} - 10^{17} Ohm·m). The most commonly used material in the application of functional sensor coatings is indium and tin oxide (ITO), the advantages of which are its transparency to the visible range of optical electromagnetic radiation and high electrical conductivity [8].

As a result of the analysis of literature sources [9, 10] for the rational mode of operation of sensor coatings of electronic devices there are certain requirements, which are the need to ensure guaranteed surface cleanliness prepared for the application of these coatings, as well as the proper choice of application.

The main problem in entering data from the projection-capacitive matrix is the strong dependence of the output signal on the type and design of the matrix, the high level of mechanical loads caused by external dynamic influences and the difficulty of adequate recognition and distinction of control signal from noise. In this case, the problem of data input from the projection-capacitive sensor matrix is the difficulty of recognizing the signal and converting it into coordinates, because the dependence of the amplitude and other characteristics of the output signal of a single segment of the matrix from distance to place is nonlinear. In addition, there are many side factors that complicate accurate coordinate recognition, such as high noise amplitude, mutual influence of matrix segments and the like. The solution to this problem is to establish the dependence of the output signals of the projection-capacitive sensor matrix on the position of the object of influence on the matrix in different methods of signal formation and measurement, as well as the development of an adequate mathematical model of analog signal conversion from the sensor matrix [11].

Therefore, the main factors that are necessary in compliance with the requirements for the quality of functional coatings are its reliable adhesion to the substrate (high adhesive and cohesive strengths that can be achieved by selecting technological modes of application of these coatings), as well as mechanical resistance and strength to external, both static and dynamic loads [9].

3. Features of determining the electrical characteristics of thin sensor coatings

Among the electrical characteristics of the ITO coating for film sensor elements should be noted the following [12-14]: electrical conductivity, resistivity, electrical capacity.

To maintain a high durability of maintaining the proper level of electrical characteristics of sensor coatings during their operation is to take into account their strength properties, which are known [15], depend on the coating material and its geometric characteristics.

Among the main geometric characteristics of functional coatings should be noted the following [16].

The geometric thickness of the coating is the shape of the controlled surface, which is characterized by a radius of curvature: $dr = 1 / S_0 \iint (Z_2 - Z_1) dS$, where S_0 – surface area of the substrate; dS is the differential element of this surface; Z_2 – surface of the substrate material; Z_1 – surface of the thin coating.

Effective coating thickness – the thickness of the coating that provides high conductivity of the surface material. Effective thickness is often associated with the measurement method. Effective in relation to this physical characteristic of the thickness is called the thickness of a homogeneous layer of a substance having the same properties as the actual coating.

In the general case, the radius of curvature dr , the effective weight thickness and the optical thickness coincide when the coating is uniform and homogeneous.

Internal and external forms of a covering. The external form is defined by the geometrical sizes of separate elements of a covering. The internal shape describes the crystal structure, type of lattice, orientation of the crystals, their size, defect, and so on.

Thus, to determine changes in the electrophysical characteristics of thin sensory coatings should take into account the following facts: the presence of donor oxygen vacancies, the presence of tin atoms, the use of colloidal metals, cationic substances, increased ionic current, increased substrate temperature, etc. [17, 18] geometric characteristics, such as geometric and effective coating thickness, internal and external forms of the coating [19], which have a significant impact on the durability of maintaining the proper level of electrical characteristics of these coatings.

4. Information and measuring stand for experimental testing of electrophysical characteristics of film sensor elements

A special information-measuring stand (IMS) was developed for experimental testing of electrical characteristics of film sensor coatings of electronic devices, where the objects of research were tested in a wide range of temperatures, humidity and dynamic mechanical loads.

The information-measuring stand (IMS) gives the chance to carry out research of electric characteristics in a wide range of values of external climatic (relative humidity and temperature) and mechanical (dynamic loading) factors. In this case, the measured values are in the range of values, which completely overlaps the range of their theoretical (calculated) values.

The general view of IMS is shown in Fig.1, and its measuring characteristics – in table.1.

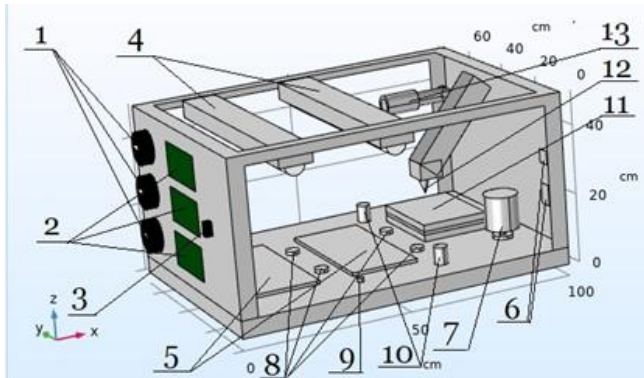


Fig.1. Appearance of the information and measuring stand: 1 - handles of adjustment of parameters of factors of influence; 2 - indicators of the stand operation status; 3 - on-off button; 4 - quartz heaters; 5 - holders for establishing the object of study; 6 - connectors for connection to a PC and to the mains; 7 - vibrating motor; 8 - ultrasonic moisture spray; 9 - microwave resonator; 10 - humidity regulator; 11 - subject table; 12 - measuring probe of electrical and mechanical characteristics from the surface of the touch screen; 13 - piezodrive of the probe (pos.12)

The main technical characteristics of the stand are as follows: operating temperature range: $-30...+80$ °C ($\pm 0.5-1\%$); relative humidity: $0-85\%$ ($\pm 2-3\%$); vibration oscillations: up to 0.45 mm/s ($\pm 3-5\%$).

Table 1. Measuring characteristics of the information-measuring stand

Measuring characteristics	Range of values	Relative measurement error, %
Specific electrical resistance, $\times 10^{-6}$, ohm·m	5 – 500	$\pm (1,5 - 2,5)$
Electric capacity, $\times 10^{-12}$, F	10 – $1,2 \cdot 10^6$	$\pm (2 - 3,5)$
Surface conductivity, $\times 10^3$, ohm ⁻¹	0,2 – 200	$\pm (3 - 4,5)$

The main element of such a stand is the control and monitoring system developed by the author, which includes two units that simulate climatic and power conditions and two measuring circuits - electrical characteristics and mechanical loads.

The principle of IMS is as follows. The object of study, was installed in special holders (pos.5), and was exposed to simultaneous thermal, vibration and humidity. The IMS was connected to a PC (pos.6), and the sensitivity and fault tolerance of the objects of the study were tested in a wide range of parameters of the above external factors in real time. According to the results of the test experiment, the researcher determined the minimum allowable probability of the operating state of the sensor sample. At the next stage, the probability of working condition of each sample was compared with their minimum allowable value. If this condition is not met, in order to increase the probability of working condition of the sensors, the researcher is given a recommendation to replace one of the established samples, the probability of failure of which has reached a minimum at the moment.

Thus, the developed test equipment (IMS) for studying the electrophysical characteristics of the film sensor elements of electronic devices, allows to determine with high accuracy the characteristics of these coatings, such as: conductivity, resistivity and capacitance. In this case, the error in determining the electrical conductivity did not exceed 4.5%, resistivity - 2.5%, capacitance - 3.5%. This allows us to draw conclusions about the rapid and qualitative determination of such electrophysical characteristics of film sensor elements in a wide range of values of mechanical (force dynamic) loads, than to adjust the operating range of values of these factors when using such sensor coatings in normal and extreme operating conditions.

5. Algorithm for determining the effect of mechanical loads on the change of electrophysical characteristics of film sensor elements

Determination of the electrical characteristics of the film sensors from the action of external mechanical loads was performed using the contact mode of interaction of the measuring probe IMS with the surface of the test sample. The adjustment of the mechanical dynamic load was performed using an adjustable electric drive IMS.

The sequence of determining the influence of external mechanical dynamic loads on the change of electrical characteristics of thin coatings.

I. Investigation of the influence of friction coefficient and adhesive strength of coatings.

1. The study of the influence of the coefficient of friction and the adhesive strength of coatings is carried out by measuring scratching (sclerometry) with a measuring probe.

1.1 The sample is mounted on a slide, which moves together with the micrometer platform for positioning or scratching in three coordinate planes, which occurs under the action of precision electric motors with built-in micrometer displacement sensors

2. In the "nanoindentation" mode, the dependence of the load on the depth of penetration of the probe is built.

2.1 There is a penetration of the measuring probe into the coating. In this case, this depth of penetration should not exceed 10-12% of the coating thickness.

2.2 Several superimposed hysteresis curves "load - immersion depth" are obtained.

2.3 The value of microhardness, modulus of elasticity and elastic recovery is calculated using specialized software (for example, "NanoTest 600").

2.4 To calculate the above module, the Oliver-Farr model is used, according to which a part of the dependence "load - depth of penetration" during unloading is described. The method consists in approximating the initial section of the discharge curve of the power function $P_{max} = B(h - h_f)^m$, where P_{max} is the maximum load, h is the depth of penetration of the indenter,

2.5 The slope of the initial stage of the unloading curve determines the stiffness of the material:

$$S = \left(\frac{dP}{dh} \right)_{h=h_{max}} = mB(h_{max} - h_f)^{m-1}. \quad (1)$$

2.6 Calculate the penetration depth of the indenter h_c :

$$h_c = h_{max} - \varepsilon \frac{P_{max}}{S}, \quad (2)$$

where h_{max} is the maximum depth of penetration of the indenter; the coefficient $\varepsilon = 0.75$:

$$H = \frac{P_{max}}{A}, \quad E_{eff} = \frac{1}{\beta} \frac{\sqrt{\pi}}{2} \frac{S}{\sqrt{A}}; \quad \frac{1}{E_{eff}} = \frac{1-v^2}{E} + \frac{1-v_f^2}{E_i}, \quad (3)$$

where v is the Poisson's ratio of the coating, the coefficient $\beta = 1.034$ - for the measuring probe; A - the projection area of the imprint is determined from the depth of the maximum penetration of the indenter h_{max} . For a diamond indenter, the Poisson's ratio $v_i = 0.07$, and the elastic model $E_i = 1141$ GPa. The amount of elastic recovery of coatings is determined by the formula:

$$W_e = \frac{(h_{max} - h_f)}{h_{max}}. \quad (4)$$

2.7 By pressing the indenter in the sample with a constantly increasing load is measured values: internal stress, acoustic emission intensity, friction force, friction coefficient and depth of scratching, Fig.2.

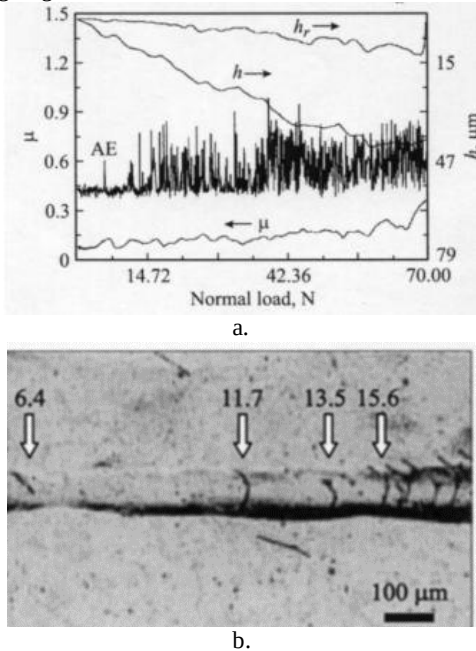


Fig. 2. The results of adhesion tests of the "coating-substrate" system: a – dependences of acoustic emission (AE), coefficients of friction μ , depth of penetration of indenter h and final depth of scratching h_f ; b – structure of the coating in the fracture zone

The procedure for testing in this method is as follows:

- 1) Before the start of the tests, the system (pendulum, load, etc.) is calibrated using a calibrated sample of fused quartz.
- 2) The test specimen is mounted on a platform stage.

3) Before the start of measurements, the sample table with the sample is brought into contact with the probe at a safe speed (3.8 μm/s), and then removed to a distance of 25 μm.

4) The measurement process is performed automatically according to a pre-prepared program (includes 10 cycles "load-unload" with a maximum value of load 200 mN and a rate of increase and decrease of load 10 mN/s with an indentation between individual contacts 20 μm along the Z axis).

5) After the measurement is completed, a software analysis of the obtained curves is performed, which allows to obtain the values of hardness, elasticity and elastic recovery of the coating.

6) The study of mechanical characteristics in depth is carried out for a batch of samples before and after each tribological examination.

7) Scratching occurs automatically according to a pre-prepared program: the load is continuously increasing from 0.5 to 200 mN at a speed of 5 mN/s; the length of the scratch is 100 μm.

8) Upon completion of scratching, a visual examination of the sample is performed - using an optical microscope and changing one of the parameters (acoustic emission, friction force, coefficient of friction, depth of penetration of the probe or final depth of scratch), fixes the moment of adhesive or cohesive destruction (critical) load, which leads to its destruction.

9) In the mode of repeated remote scanning of the surface, get a map of the distribution of residual electric charge on the surface of the study area.

10) With the help of specialized software, the values of capacitance, electrical conductivity and surface resistance are calculated.

Thus, a method for studying the effect of external dynamic mechanical loads on the electrophysical characteristics of sensor coatings obtained using the developed IMS, the use of which allows to establish the effect of dynamic mechanical loads on the electrophysical characteristics (conductivity, resistivity and capacitance of the sensory coating) of electronic devices.

6. Analytical modeling of electrical processes occurring in the coatings of sensor elements from the action of mechanical loads

Under conditions of thermodynamic equilibrium, the calculation of the electrical characteristics of the p-n junction, namely: the built-in electric field and the distribution of charge carriers, is based on the Poisson equation:

$$\frac{d^2\phi(x)}{dx^2} = \frac{4\pi e}{k_0} [n(x) - N_d - p(x) + N_a(x)], \quad (5)$$

where, $\phi(x)$ is the electrostatic potential, e is the elementary charge, k_0 is the static dielectric constant.

The concentration of donors $N_d = \text{const}$ corresponds to a homogeneous n-doping of the original sample, and the concentration of acceptors $N_a(x)$ is determined by the parameters of ion doping.

It is believed that all donor and acceptor levels are ionized. If the degeneracy of the charge carriers of the concentration of electrons $n(x)$ and holes $p(x)$ is arbitrary, then they are self-consistently associated with the electrostatic potential, according to the following relations:

$$n(x) = N_c F_{1/2} \left[\frac{\varepsilon_F - g_a + e \cdot \phi(x)}{k_B T} \right]; \quad (6)$$

$$p(x) = N_v F_{1/2} \left[\frac{-\varepsilon_F - g_a - e \cdot \phi(x)}{k_B T} \right]. \quad (6')$$

where $N_{c,v} = \frac{\sqrt{2} (m_{c,v} k_B T)^{3/2}}{\pi^2 h^3}$ is the effective density of states in the conduction band (c) and the valence band (v), m_c is the effective mass of the electron, m_v is the effective mass of the holes, h is the Dirac constant and T , g_a is the temperature and absolute humidity of the environment, and the functions $F_{1/2}$ are Fermi-Dirac integrals.

Equations (6)-(6') are obtained under the assumption of the parabolic law of carrier dispersion, where ε_g is the band gap.

Equations (5)-(6') form a nonlinear differential equation of the second order, which for an arbitrary thin layer $N_a(x)$, is possible to solve by the finite element method, within the Cauchy problem with boundary conditions.

$$\varphi(-L'_n) = 0, \varphi(-L'_p) = \Phi_b, \quad (7)$$

In the depth of the quasi-neutral n-region, a zero potential equal to a certain value of Φ_b (height of the built-in electrostatic potential) is selected. The constants Φ_b and ε_F are unknown, but must satisfy the conditions of charge neutrality within the $n(x = -L_n)$ and $p(x = L_p)$ domains.

It is known [20] that the region of the spatial charge has a size of about 1.5-2 μm . In this case, the potential distribution shows a bimodal behavior that is absent for the standard profile of the sensory n - p junction with sharp doping. The resulting size of the space charge region is proportional to the characteristic length of the absorption of infrared radiation, which makes it possible to detect infrared radiation.

In regions deeper than 3 μm , a quasi-neutral n-region is realized, where the concentrations of the main carriers (electrons) are approximately N_d , and the concentration of non-basic carriers (holes) is orders of magnitude lower than in the p-region. It is important to note that in the depth of the p-region the electron gas of the holes remains degenerate (the Fermi level lies in the valence band).

To describe the transfer of carriers in the electric p - n junction, a drift diffusion model is used, which characterizes the following system of equations:

$$\frac{d^2\varphi(x)}{dx^2} = \frac{4\pi e}{k_0} [n(x) - N_d - p(x) + N_a(x)]; E(x) = -\frac{d\varphi}{dx} \quad (8)$$

$$j_n(x) = e\mu_n n(x)E(x) + eD_n \frac{dn(x)}{dx} \quad (9)$$

$$j_p(x) = e\mu_p p(x)E(x) + eD_p \frac{dp(x)}{dx} \quad (10)$$

$$\frac{1}{e} \frac{dj_n(x)}{dx} = -(G^+(x) - G^-(x)); \frac{1}{e} \frac{dj_p(x)}{dx} = (G^+(x) - G^-(x)); \quad (11)$$

$$j \equiv j_n(x) + j_p(x) = \text{const} \quad (12)$$

where j_n and j_p are the partial currents of electrons and holes, respectively (total current through the p-n junction is a constant), and $\mu_{n,p}$ and $D_{n,p}$ are their mobility and diffusion coefficients.

In the case of a nonequilibrium state, the concentrations of electrons and holes are determined by the local quasi-Fermi levels $\varepsilon_n(x)$ and $\varepsilon_p(x)$, which are functions of coordinates:

$$n(x) = N_c F_{1/2} \left[\frac{\varepsilon_n(x) \cdot g_a^{2/3} + e \cdot \varphi(x)}{k_B T} \right]; \quad p(x) = N_v F_{1/2} \left[\frac{-\varepsilon_p(x) \cdot g_a^{1/3} - \varepsilon_g - e\varphi(x)}{k_B T} \right] \quad (13)$$

In the equation of continuity 12, the values of $G^\pm(x)$ correspond to the generation and recombination of electron-hole pairs. The model of direct generation and recombination was used, within which $G^\pm(x) - G^\mp(x) = -\gamma[n(x)p(x) - n_0p_0]$ where γ is the volume recombination coefficient. Equation (13) is supplemented by boundary conditions that assume a model of ohmic contacts:

$$\varphi(-L'_n) = 0; \varphi(-L'_p) = \Phi_b + \frac{U_D}{e};$$

$$\varepsilon_n(-L'_n) = \varepsilon_p(-L'_n) = \varepsilon_F; \varepsilon_n(L'_p) = \varepsilon_p(L'_p) = \varepsilon_F - U_D, \quad (14)$$

where the equilibrium parameters Φ_b and ε_F can be obtained from the previous section, and U_D is the applied voltage.

When calculating the volt-ampere characteristics, it is taken into account that the recombination times of holes in the n-region and electrons in the p-region depend on the corresponding concentrations. Therefore, the recombination coefficients in the n - and p -domains can be expressed as $\gamma_n(x) = [\tau_p(\varepsilon_F \cdot g_a + \varepsilon_g + e \cdot \varphi(x))n(x) - 1]$ and $\gamma_p(x) = [\tau_n(\varepsilon_F \cdot g_a + \varepsilon_g + e \cdot \varphi(x))p(x) - 1]$, respectively.

As a result, $\gamma(x) = \gamma_n(x)$ for $x < x_{ch}$ and $\gamma(x) = \gamma_p(x)$ for $x > x_{ch}$ is characterized by a coordinate at which $\gamma_p(x_{ch}) = \gamma_n(x_{ch})$.

It is seen that $\gamma(x)$ in the n - and p -domains takes the values $\gamma \approx 10^{-9}$ and $\gamma \approx 3 \cdot 10^{-10} \text{ cm}^3/\text{s}$, respectively and significantly increases its values to $10^{-5} \text{ cm}^3/\text{s}$ in the region of space charge. As calculations have shown, the quasineutral region can be considered as part of the contact resistance R_c .

Thus, the analytical dependences of electrical processes occurring in the functional coatings of the sensor elements of electronic devices are obtained. However, some differences in analytical calculations can be explained by several factors that do not take into account the classical theory. In particular, such film sensor elements may have additional current transfer mechanisms that may be associated with barrier tunneling effects, electrical breakdown effects caused by strong internal fields, and so on. Classical theory also does not take into account leakage currents through surface states in the real two-dimensional configuration of the sensor element.

7. Development of a computer mathematical model of the electrophysical characteristics of sensory elements

To study the electrical properties of electrically conductive thin ITO film, the finite element method is used. In this case, numerical simulation of the electrical properties of a 3D model of a thin touch film is performed using Comsol Multiphysics.

To implement the finite element method, Maxwell's equation is used in terms of electric potential:

$$-\nabla \times \left(\left(\sigma + \varepsilon_r \varepsilon_0 \frac{\partial}{\partial t} \right) \nabla \varphi \right) = 0 \quad (15)$$

where, σ is the electrical conductivity of the material; ε_r – relative dielectric constant; ε_0 – vacuum dielectric constant ($8.854 \times 10^{-12} \text{ F/m}$);

After that, the problem was reduced to solving the electric potential in each region of finite elements.

Other electrical characteristics, such as resistivity (Z) and electrical capacitance (C), can be determined by the following formulas, respectively:

$$Z = \frac{1}{\gamma} = Z' + jZ'' \quad (16)$$

$$C = C' + jC'' = \frac{\gamma''}{\omega} + j \frac{\gamma'}{\omega} \quad (17)$$

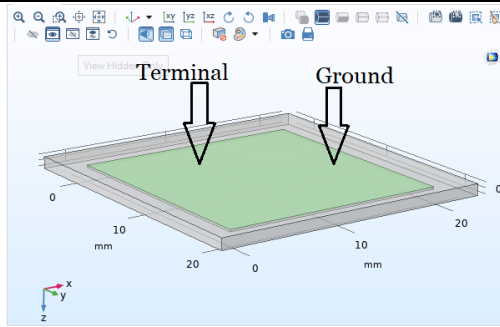
In this case, the modeling of the ITO film is considered as a homogeneous layer without defects and porosity.

The procedure for setting up simulation in Comsol Multiphysics is as follows:

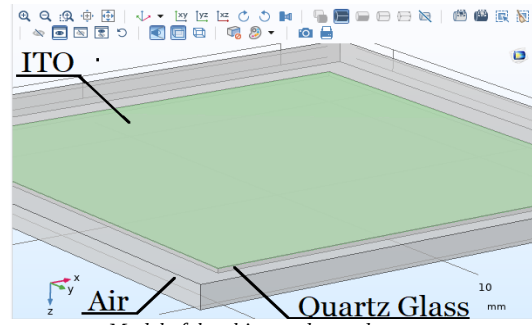
- the 3D model and the interface of electric currents AC/DC are selected in the Comsol modeling menu;
- geometric modeling of a thin film is carried out;
- an appropriate modeling grid is created;
- the electrical parameters of the test material are determined;
- the model is calculated by the correct expression in the study of the frequency domain.

There is a final transformation of the calculated data into other electrical properties.

The results of numerical studies. In the proposed computer model, the upper plane of the object is the electrode of the sensor element. ITO film ($20 \text{ mm} \times 20 \text{ mm} \times 10 \mu\text{m}$) is applied on top of the substrate (quartz glass: $20 \text{ mm} \times 20 \text{ mm} \times 0.2 \text{ mm}$), which is surrounded by air ($25 \text{ mm} \times 25 \text{ mm} \times 1 \text{ mm}$). This model (Fig. 3) best mimics the real object of study.



Geometric parameters of the 3D model for configuring measurements in the plane



Model of the object under study (film sensor element)

The low electrical potential of the surface of the ITO film is installed on the conductive substrate, except for the area in the area of the electrodes. The largest dispersion of the electric potential for the insulating substrate is demonstrated near the region of the electrodes. It should also be noted that when measuring the ITO film on the conductive substrate, only the ITO region and the single crystal substrate have a significant effect on the current direction.

Simulated impedance and capacitance values from 0.1 Hz to 10 MHz for the same 10 μ m ITO film also demonstrated that the measurement configurations can cause very large differences in the electrical characteristics of this film, Fig. 4.

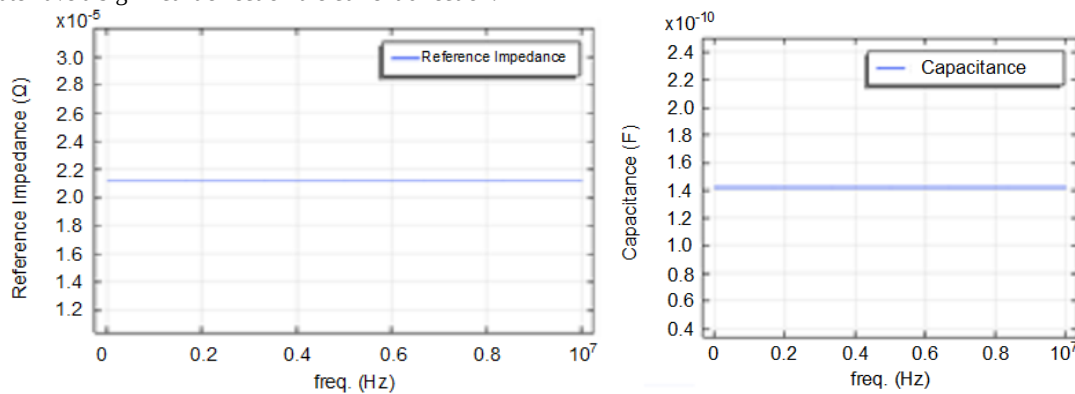


Fig. 4. The results of the calculation of the impedance (left) and capacitance (right) for the ITO sensor film in the frequency range $10^{-1} - 10^6$ Hz

For example, the impedance values of 1 Hz for ITO film (20 mm × 20 mm × 10 μ m) can vary from $5,247 \cdot 10^{-5}$ Ohms for parallel plate configuration to 100.8 Ohms for in-plane measurements on insulating material. The actual capacitance at an operating frequency of 1 Hz can vary from $5.712 \cdot 10^{-4}$ μ F (plate thickness) to about 10^{-3} pF (along the plane). These values can also be used to verify the accuracy of the model. According to the equations of resistance and capacitance for parallel plates 4 and 5 were:

$$R = \frac{\rho L}{A} = \frac{t}{\sigma a^2} = \frac{10 \cdot 10^{-6}}{1180 \cdot (20 \cdot 10^{-3})^2} = 2,118 \times 10^{-5} \text{ ohm}$$

$$C = \frac{\epsilon_r \epsilon_0 A}{d} = \frac{\epsilon_r \epsilon_0 a^2}{t} = \frac{4 \cdot 8.854 \cdot 10^{-12} \cdot (20 \cdot 10^{-3})^2}{10 \cdot 10^{-6}} = 1,416 \times 10^{-10} \text{ F}$$

Thus, the simulation results show that the configuration of the parallel plate and the configuration in the plane with the conductive substrate show a relatively low value of impedance. Given the existence of conductor resistance and contact, it is very difficult to obtain a real electrical reaction of the ITO film from the results of real experimental measurements. In addition, at very low resistance, the imaginary impedance of the circuit will be dominated by the inductance of the circuit, which can not show the correct capacitive behavior. Thus, the measurement in the plane with the insulating substrate, which has a relatively large value of impedance - minimizes the impact of the environment.

Influence of material and air environment. As insulating materials, the quartz glass substrate and the air environment have high impedance values in real conditions. Simplified 3D models were used to model the impedance and capacitance of a combination of ITO film with a quartz substrate, a combination of ITO film with air, a combination of ITO with both a substrate and

air. Thus, it became possible to divide and compare the electrical characteristics of each material. Thus, the quartz substrate and the air layer are insulated, and their impedances decrease with increasing frequency. The ITO film with a thickness of 10 μ m and its three combinations with the surrounding materials had the same impedance of 10^4 Ohms. Imaginary impedances have always been close to zero compared to real impedances. Thus, the value of the calculated impedance is close to the actual value of the real impedance. Thus, it was concluded that the material and the air have little effect on the impedance of the ITO film.

However, the values of the received capacities showed different tendencies. Thus, clean substrate ($3.15 \cdot 10^{-14}$ F) and clean air ($7.51 \cdot 10^{-15}$ F) have a much larger capacity than pure ITO film ($3 \cdot 10^{-18}$ F, within the estimate of 10^{-19} F to 10^{-17} F). As a result, the capacities of the combined systems are close to the substrate capacity and the air capacity, more than two orders of magnitude higher than the capacity of the ITO film, even showing a transition in the middle frequency range (10 to 10^4 Hz).

8. Comparison of the results of analytical and mathematical modeling of the electrophysical characteristics of sensory elements from the action of mechanical loads

The comparison of the results of analytical and mathematical modeling is presented in Fig. 5, shows the difference between simulation under thermodynamic equilibrium and simulation using the finite element method.

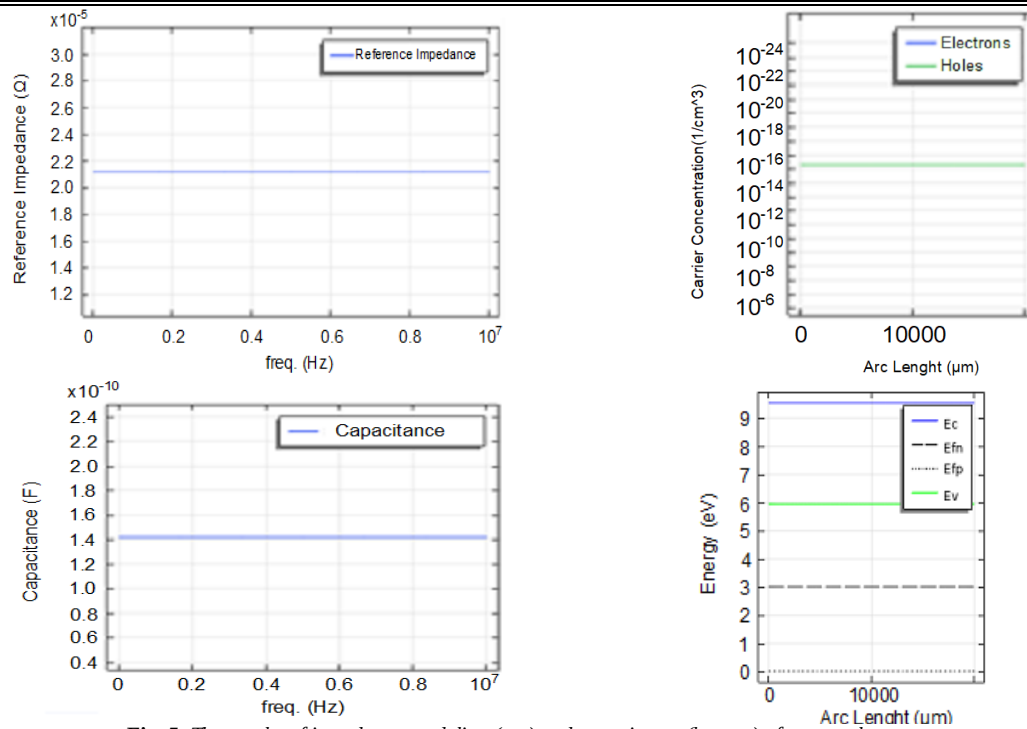


Fig. 5. The results of impedance modeling (top) and capacitance (bottom) of sensor elements:

on the left - the results of numerical modeling, on the right - the results of analytical modeling:

E_c - conduction band energy level; E_{fn} - electron quasi-fermi energy level; E_{fp} - hole quasi-fermi energy level; E_v - Valence band energy level

The simulation was performed using COMSOL software. A two-dimensional semiconductor model was used for analytical modeling, namely, the energy zones for the semiconductor and the frequency properties of the p-n junction were studied.

A three-dimensional model of a thin-film semiconductor was used for numerical simulations, namely: resistivity, electrical conductivity and electrical capacitance were studied.

The results obtained as a result of modeling the electrophysical characteristics of the sensor device take into account the results of stationary and frequency studies.

The main task of the study was to measure the characteristics to identify the performance of the sensor device in extreme conditions.

Thus, as a result of mathematical modeling of electrical processes occurring in the film sensor elements of electronic devices from the action of mechanical loads, the study of electrophysical processes occurring under normal and extreme conditions is performed.

Analytical and numerical modeling of the investigated surface of the sensor device was performed.

In the case of analytical modeling, the electrical characteristics of the p-n junction of the investigated semiconductor were calculated, namely the built-in electric field and charge carrier distribution from changes in internal voltages and, accordingly, the carrier concentration in the semiconductor.

In the case of numerical simulation, the COMSOL software was used, which allows to do research by the finite element method, which uses the Maxwell equation, in terms of electric potential. Measurement of electrical conductivity, capacitance and resistivity was performed in the frequency range 10^{-1} – 10^7 Hz, in the conditions of finding the sensor coating on the insulating substrate in the ambient air.

5. Conclusion

As a result of research the following is established:

- increasing the mechanical load on the thin-film sensor element with a simultaneous decrease in the interaction time with a constant contact area leads to an exponential increase in power and sensitivity of the reaction pulse, provided that such mechanical load

does not exceed the mechanical strength of the sensor element material;

- increase in mechanical load on the sensor element for a constant time and contact area, almost does not change the sensitivity of the reaction pulse (maximum increase in sensitivity does not exceed 1.8%);

- vibrational oscillations in the frequency range of 30-85 Hz at mechanical forces of the order of 20-150 mN create response pulses of the order of 12-45 mV/μs, which are perceived as "false operation" of sensor elements;

- increasing the frequency and mechanical forces above the specified range leads to the destruction of the base of the sensor element and the detachment of the sensor film from the base;

- reduction of frequency and mechanical forces below the specified range create reaction pulses up to 12 mV/μs, which does not exceed the permissible values of "white noise" (about 25-35% of the minimum value of the reaction pulse).

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A high-performance Ti-Zr BASED conversion coating on 5556 aluminum alloy

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Abstract: The process of deposition of titanium, zirconium-containing coatings at aluminum alloy 5556 is developed. In the process of performing the work, the basic patterns of coating formation were identified. The solution composition and process parameters were optimized, and the physicochemical properties were investigated. It is shown that passivation of aluminum alloy 5556 in a titanium, zirconium-containing solution increases its corrosion resistance to pitting corrosion. These coatings can replace chromate coatings because of good ability to resist corrosion.

KEYWORDS: CORROSION PROTECTION, CONVERSION COATINGS, TITANIUM-CONTAINING COATINGS, ZIRCONIUM-CONTAINING COATINGS, SURFACE TREATMENT, CHROMATE-FREE PASSIVATION

1. Introduction

Aluminum alloys are widely used as a structural material in various fields of technology, in industrial and civil construction for the manufacture of building frames, window frames, stairs, in the automotive industry, in shipbuilding, aviation and space technology, in electrical engineering, in nuclear reactor construction, etc. [1]. Due to the presence of a thin natural oxide film on the surface, aluminum and its alloys are sufficiently resistant to corrosion, therefore, in some cases, they are used without special anti-corrosion protection. However, due to its low thickness, the natural film on the surface of aluminum often does not provide reliable protection against corrosion, for example, in a humid industrial atmosphere or in sea water.

Conversion chromate coatings are widely used as thin-layer adhesive layers under paint coatings before painting aluminum and its alloys.

Due to the high toxicity of chromating solutions, which include highly toxic hexavalent chromium compounds, and the conversion coatings formed in them, which also contain up to 200 mg/m² of Cr⁶⁺, the legislation of many States significantly restricts or completely prohibits the use of conversion chromate coatings.

In the recent years in the world practice nanoscale particles obtained from hexafluorozirconic and hexafluorotitanic acids are more and more often used as an alternative to chromate layers [2-5]. Currently, world leading companies are actively developing the technologies necessary for production of such surfaces.

The development of protective and adhesive titanium, zirconium -containing conversion coating application methods on 5556 alloy with the aim replacing toxic chromating processes in automobile industry is the goal of the current work

2. Prerequisites and means for solving the problem

For the application of conversion coatings, samples of an aluminum alloy AA 5556 widely used in the automotive industry of the size of 3x4 cm were used.

Passivating coatings were formed by immersing aluminum samples in the test solution for a specified time, after which the samples were removed and dried by blowing hot air at a temperature of 80° C for 10 minutes.

For the deposition of chromate coatings, which were selected as objects of comparison, a solution containing 15 g/l Na₂Cr₂O₇ and 60 g/l Na₂CO₃ (T= 95-100 °C; τ=20-30 min) was used.

To accelerate the evaluation of the protective ability of conversion coatings, a drop-express method was used using an Akimov solution containing: CuSO₄·5H₂O 82 g/l, NaCl 33 g/l, 0.1 N HCl 13 ml/l. The PAA (Akimov's protective ability) of conversion coatings on aluminum or its alloys is estimated by this method as time (in seconds) before the color change at the surface under a drop from gray to black.

The thickness of the coatings was determined by an ellipsometric method using a spectroscopic ellipsometer by Sentech SENreasech (SENTECH Instruments GmbH, Krailling, Germany)

4.0 SER 800 with a high-speed monochromator. The measurements were carried out in the spectral range of wavelengths of 240–1000 nm at a goniometer angle of 70° [6].

The composition of the surface layers was studied using X-ray photoelectron spectroscopy (Omicron, Taunusstein, Germany) (XPS). The panoramic spectra were also recorded after argon-ion etching of the coating in different depths. Thus, the composition of the coating at different distances from the substrate was determined. The pressure of the inert gas in the working chamber was maintained at this level, so that the ion energy and the ion current rate, and consequently, the etching rate, were constant. When analyzing the obtained spectra, it was considered that the analyzing beam penetrates the material to the depth of 5 nm, i.e., the resulting spectra correspond to a layer of material 5 nm thick.

The adhesion of the coatings was determined by the normal detachment method using the PosiTest AT digital adhesion meter. The method is based on measuring the minimum breaking tension required to separate or rupture the coating in a direction perpendicular to the substrate surface [ASTM D4541-17].

Pitting corrosion tests were carried out by simulating the effects of the maritime climate in constant contact with seawater. The test samples were immersed in a solution containing 3% sodium chloride and 0.1% hydrogen peroxide in accordance with GOST 9.913-90.

The study of the surface morphology of the coated samples was carried out using an MPLAPONLEXT 100 objective on a LEXT - OSL 4100 confocal laser microscope. To assess the layer structure, the degree of surface development, the depth and width of pitting corrosion spots, the surface images and profilograms of the samples after the formation of the conversion coating were investigated. The measurements were carried out in two-dimensional and three-dimensional coordinate systems.

Corrosion tests were carried out in a salt spray chamber Ascott S450iP in accordance with the international standard ASTM B117.

3. Solution of the examined problem

As a result of this work, in order to replace the toxic chromating process in the automotive and other industries, a solution for applying protective titanium-, zirconium-containing coatings on the surface of the 5556 aluminum alloy based on H₂TiF₆, H₂ZrF₆, Ce(NO₃)₃ was developed.

In the process of research, the main patterns of the formation of coatings were revealed. Optimization of the composition of the solution and process parameters was carried out. The physicochemical properties of the coatings were investigated with the aim of their application as a substitute for chromate coatings.

Coatings with the best physical and chemical characteristics are formed in a solution with pH=4.0-5.0 at room temperature in 2 minutes of the process.

The chemical composition of the coatings was investigated with the help of X-ray photoelectron spectroscopy. The survey spectra of the coatings indicate the presence of titanium, zirconium, aluminum, cerium and oxygen in the coating.

Separate spectra of the elements made it possible to establish in which compounds the indicated elements are included in the coating (Fig. 1).

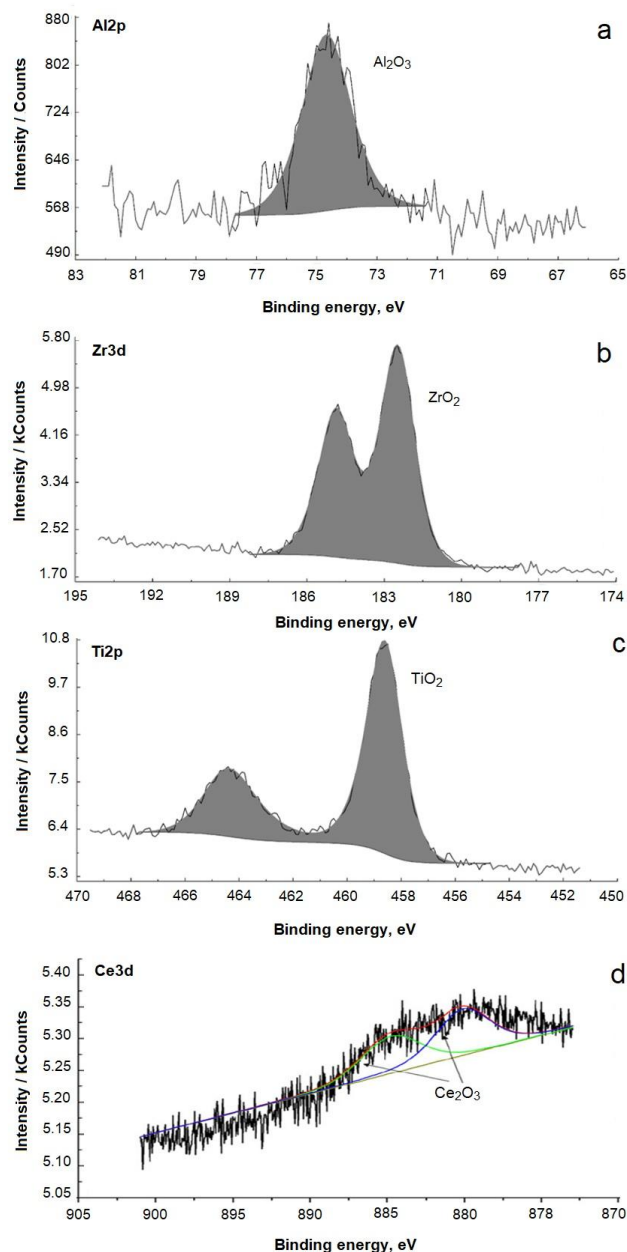


Fig. 1. Individual XPS spectra of aluminum (a), zirconium (b), titanium (c), cerium (d)

Aluminum is present in the coating in the form of Al_2O_3 oxide. Zirconium and titanium are present in the coating in the form of ZrO_2 and TiO_2 oxides. The position of the cerium energy peak corresponds to Ce_2O_3 .

Results and discussion

Corrosion tests (ASTM B117) in a salt spray chamber of painted samples of 5556 aluminum alloy with an adhesive Ti, Zr-containing coating were carried out. Tests have shown that Ti, Zr-containing coatings formed in the developed solution meet the

requirements in terms of protective ability, since the width of corrosion penetration from the notch does not exceed 2.0 mm after 750 hours of testing. It should be noted that in terms of corrosion properties these coatings are not inferior to chromate ones.

Corrosion tests of separate anticorrosive Ti, Zr-containing coatings showed that the coatings formed on the 5556 alloy in a Ti, Zr-containing solution have the highest resistance. The first corrosion spots appear after 170 hours of testing, while on the 5556 alloy with chromate coating they appear after 160 hours, and on the 5556 alloy after 24 hours of testing.

It was found that the inclusion of cerium-ions improves the resistance of the coating to pitting corrosion. The thickness of Ti/Zr/Ce-containing coatings is 120 nm.

With the help of confocal microscope the morphology and surface profile of the resulting coatings after corrosion tests in a $NaCl+H_2O_2$ solution were studied. It was found that the first pitting corrosion spots appeared in the unprotected 5556 alloy - 216 hours from the start of testing. Further pitting appeared on the Ti/Zr-containing coating - 1830 hours. After 2000 hours of testing corrosion was not observed on the Ti/Zr/Ce-containing and chromate coatings. During this time, the average depth of pitting corrosion spots was 206 μm for the 5556 alloy and 16 μm for the 5556 alloy with a Ti/Zr-containing coating.

4. Conclusion

The developed solution containing in its composition 1.2 g/l H_2TiF_6 and 1.2 g/l H_2ZrF_6 is a good alternative to toxic chromating solutions for protecting the aluminum surface from atmospheric corrosion and can also serve as an adhesive coating.

The developed solution containing in its composition 1.2 g/l H_2TiF_6 , 1.2 g/l H_2ZrF_6 and 1 g/l $Ce(NO_3)_3$ is a good alternative to toxic chromating solutions for protecting aluminum surface from pitting corrosion.

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Attenuation of ultrasonic shear waves in polymeric materials

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Abstract: Ultrasonic non-destructive method has been applied to investigate different types of optical polymeric materials. Attenuation coefficients and paths lengths of normal incidence shear waves in the materials have been determined by means of the pulse-echo multireflection technique. Comparison among acoustic properties of the examined polymers and the standard polymethyl methacrylate test sample at 5MHz frequency is carried out. Obtained results are used to qualify homogeneity and isotropy of studied materials.

Keywords: PULSE-ECHO METHOD, ULTRASONIC ATTENUATION COEFFICIENT, OPTICAL POLYMERS, NORMAL INCIDENCE SHEAR WAVES

1. Introduction

Nowadays, polymers are widely used in all areas of industry, science, medicine, domestic consumption, etc. In many applications, they are preferable to traditional materials mainly because of their low cost and weight. Excellent electrical and thermal insulation properties of plastics, high abrasion and corrosion resistance, good transparency in optical applications are an essential issue for their usage, too [1].

In this paper, eight types of thermoplastic optical polymers have been investigated applying normal incidence ultrasonic shear waves. Velocity and attenuation of ultrasonic waves are the most important parameters for material characterization [2, 3]. Obtained values and the frequency dependence of these two quantities are related to composition and structure of the medium as well as to the different mechanism of interaction of sound waves with substance particles. The ultrasonic study of a material provides information about elastic constants, structural inhomogeneities, mechanical and thermal properties under different conditions, etc. [3].

We have determined velocities and attenuation of the longitudinal ultrasound waves propagating through the optical polymeric materials [4]. The measurements of thin walled plastic samples were carried out at frequencies of 2.25 MHz, 5.0 MHz, 10.0 MHz [5] and 15MHz [6]. In this report, ultrasonic shear waves were used to obtain additional information on acoustic properties of polymers.

2. Experiment

Several types of transparent polymeric materials have been studied: acrylic, styrene acrylonitrile (SAN), low-molecular weight S-low Styrene, cellulose and some trade-marks as Optorez 1330, Zeonex E48R and Bayer. Samples were prepared as plane-parallel plates with thickness varying from 2.00 mm to 5.58 mm.

Ultrasonic investigations of studied polymers have been carried out by means of Krautkramer flaw detector USM 35XS. A pulse-echo contact ultrasonic method was applied and a 5 MHz, SONIC transducer with effective diameter Ø 6 mm was used as both transmitter and receiver of the ultrasonic signal. The transducer is aligned on the Krautkramer test specimen, made of polymethyl methacrylate (PMMA) and the detector is adjusted to obtain a maximal number of back echoes, clearly observed on the time axis at the display. The fixed time interval is set the same during the measurements of all studied polymers. Attenuation (the sensitivity level) in dB of shear ultrasound waves in the samples was determined at level of signal amplitude of 80% of F.S.H. (Full Screen Height).

3. Results and discussion

In Table 1 the number of back echoes and the sound path length L in studied polymers are presented. The total attenuation coefficient α is estimated by the well-known equation:

$$(1) \quad \alpha = -\frac{1}{L} \lg \frac{A_0}{A_L},$$

where A_0 and A_L are the signal amplitudes at $x = 0$ and $x = L$, respectively. Results are included in the table. The thickness d of samples is also indicated.

Table 1: Sound path lengths and attenuation coefficients of polymeric materials.

Optical polymer	d , mm	Number of echoes	L , mm	α , dB/mm
PMMA (test sample)	2.00	4	16.00	2.98
SAN	2.77	4	22.16	2.20
Optorez 1330	2.01	4	16.08	2.92
S-low styrene	3.07	2	12.28	4.28
Zeonex E48R	2.07	2	8.28	6.67
Bayer	2.51	1	5.02	7.83
Cellulose	4.65	1	9.30	4.74
Acrylic	5.58	1	11.16	4.75

In case of plastics, the energy decrease of ultrasonic wave is due mainly to absorption. It is related to the structure and homogeneity of the material and depends on the wave frequency. Obtained results are compared to the Krautkramer test PMMA sample. This polymer is typically used as a delay line in ultrasonic non-destructive testing and its acoustic properties are well investigated and guaranteed by the producer. The test specimen gives many clearly defined reflected signals in the defined time interval and consequently has low acoustic resistance.

Table 2 shows the required increase in sensitivity in dB, compensating the damping of ultrasound waves for multiple passes of the distance in the studied polymeric samples. The number of rows corresponds to the number of registered echoes in each sample.

Table 2: Adjusting the sensitivity in dB for different types of polymers in respect to the registered back pulse echoes.

Optical polymer	Compensating increase in sensitivity, dB			
PMMA	30.6	34.1	41.4	47.6
SAN	26.2	36.9	45.4	48.8
Optorez 1330	24.5	31.4	41.4	47
S-low styrene	36.5	52.5	-	-
Zeonex E48R	38.5	55.2	-	-
Bayer	39.3	-	-	-
Cellulose	44.1	-	-	-
Acrylic	53.0	-	-	-

As low the required increase in sensitivity is, the lower the acoustic resistance of the polymer is. As seen, at lowest damping

best results are obtained for the Optorez and SAN samples as well as for the Krautkramer test specimen. It is interesting to note that the acrylic polymer produced by the American Eastman Chemical Company (ECC) has much higher damping than the test specimen which is acrylic type, too. However, the thicknesses of the two specimens are rather different. The thicker the sample the stronger absorption is observed and less back wall echoes are registered. The difference in the results for both acrylic specimens may be due also to the production conditions as degree of polymerization, processing temperature, moulding injection rates and pressure, cooling time, etc. as well as to the used additives as plasticisers, mould release agents and brand peculiarities. As a result acoustic properties of different types of a given polymer may vary significantly.

Attenuation of the wave signal at corresponding back echoes is visualised in Fig.1. Along the abscissa axis the number of echoes is given for each material while damping is indicated at the ordinate axis. As it can be seen, studied polymers can be divided in three groups. Test PMMA specimen, SAN and Optorez 1330 samples show similar acoustic characteristics and form the first group. The numbers of registered back wall echoes in these materials are 4 and attenuation coefficients are with small values below 3 dB/mm (Table 1). Results for Optorez almost coincide with those of the test sample for the third and fourth reflected signals and the ultrasound path length is up to 16 mm.

Among studied polymers, the SAN material is with the lowest values of attenuation coefficient (Table 1). The thickness of the sample is about 1.4 times greater in comparison to the other two plastics in the group and therefore, the decrease of wave energy at the opposite surfaces is smaller. The number of back wall echoes indicates the negligible relaxation time of the medium in comparison to the durability of the wave propagation which means that the polymer remains practically in equilibrium state. The results for SAN and Optorez samples reveal high acoustic homogeneity of their structure.

The second group in Fig. 1 consists of the Zeonex E48R and S-low styrene samples. For these polymers the attenuation coefficients are 6.67dB/mm and 4.28dB/mm at 2 registered echoes, respectively. Results show that absorption in these materials is high with initial attenuation of the signal over 50 dB (Table 2).

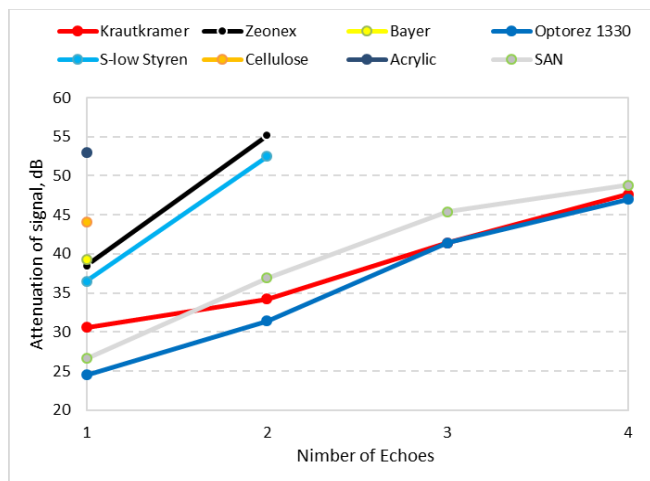


Fig. 1 Signal attenuation in dependence of the number of registered back echoes

The acrylic and cellulose polymers of ECC are with relatively low attenuation coefficients and form the third group. The samples are much thicker in comparison to the rest specimens and therefore, the number of echoes is restricted and lower energy losses due to reflection at opposite surfaces occur. The energy decrease is determined mainly by the absorption in media with high acoustic resistance. The Bayer can be also assigned to this group with one echo in the sample but greater value of coefficient α .

4. Conclusions

The conducted experiments show that the applied non-destructive testing method can serve as a comparison between the different polymeric materials in terms of structure and homogeneity, as well as for quality testing of samples through the so called "Express-analysis" without disturbing their integrity. The co-application of this method with optical and mechanical measurements ensure a better study and correct selection of polymeric materials in respect to their applications in various optical, electro-optical and acoustic optical devices.

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