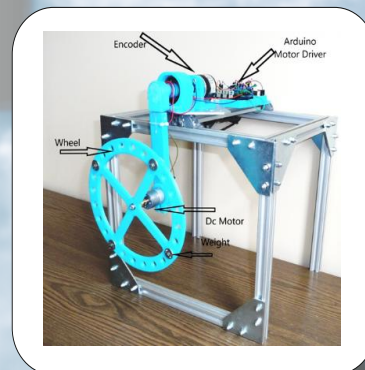


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Dynamic analysis of a four-bar linkage mechanism

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Abstract: In the present paper, dynamic analysis of rigid four-bar linkage has been studied. Equation of motion has been obtained by using Lagrange's Equation. Dynamic behavior of four-bar linkage has been analyzed using MATLAB/Simulink. Angular kinematics of each member of linkage have been determined.

Keywords: FOUR-BAR LINKAGE, DYNAMIC ANALYSIS, LAGRANGE FORMULATION, ANGULAR KINEMATIC.

1. Introduction

Four-bar linkages are the mostly used mechanism in industry and machine design. Smaller linkage mechanisms became more effective with technological development because of reducing the crank weight and high operating speed in machinery. Therefore, dynamic analysis of variable forces, inertial effects and external torques on four-bar mechanisms has been carried out by researchers over the years. Freudenstein [1] was founder of the modern kinematics and with his contribution kinematic synthesis of mechanisms became applicable using digital computation. Neubauer et al. [2] investigated the transverse vibrational characteristics of the connecting rod in a slider-crank mechanism. Smith and Maunder [3] studied the undamped transverse vibration of a flexible coupler in a four-bar linkage which is governed by an inhomogeneous Hill's equation. Sadler and Sandor [4] developed a method of kineto-elastodynamic analysis employing lumped parameter models for simulating moving four-bar mechanism components subject to elastic bending vibrations. Furuhashi et al. [5–8] described a general theory of dynamics of four-bar linkage with clearances at all turning pairs using a continuous contact model. Zobairi and Sahay [9] investigated the contribution of kineto-elastodynamic inertia forces toward the shaking force and shaking moment along with the contribution of the rigid-body inertia forces while balancing a four-bar mechanism by internal mass redistribution. Yang and Krishnaprasad [10] studied the kinematics and dynamics of floating, planar four-bar linkages. Effect of dynamic balancing on four-bar linkage vibrations is investigated by Xi and Sinatra [11]. Karkoub and Yigit [12] studied dynamic modeling and controller design for a flexible four-bar mechanism. They obtained the fully coupled nonlinear equations of motion through a constrained Lagrangian approach. Yan and Soong [13] presented a novel method for four-bar linkages which satisfies kinematic design requirements and also attains trade-off dynamic balance. Kilinc [14] studied dynamic modelling for an elastic four-bar mechanism. Differential-algebraic equations of motions are solved numerically by Simulink to obtain the system response. Tang [15] showed the formulation steps of the dynamic equation of a four-bar mechanism in the minimal coordinate form using Lagrangian formulation.

In the present study, equations of motions of the four-bar linkage with geometrical constraints have been obtained using Lagrangian equations. Systems of nonlinear equations have been solved with Simulink program. Solution process of governing equations have been carried out with only one MATLAB function, differently from literature search. Variation of angular displacement, velocity and acceleration of each link with angular position have depicted in figures. Different initial positions have been taken into consideration.

2. Analysis

2.1. Position Constraints in Four-Bar Linkage

Consider a four-bar linkage mechanism (Figure 1). There are two geometrical constraints for the linkage mechanism that can be seen in Eqs. (1) and (2):

$$L_2 \cos \theta_2 + L_3 \cos \theta_3 - L_4 \cos \theta_4 = L_1 \quad (1)$$

$$L_2 \sin \theta_2 + L_3 \sin \theta_3 = L_4 \sin \theta_4 \quad (2)$$

Angular displacement of 3rd and 4th links can be defined as a function of θ_2 using the constraints in Eqs. (1) and (2). Sum of squares of the constraints equations give the well-known Freudenstein Equation [16]:

$$P_1 \sin \theta_4 + P_2 \cos \theta_4 + P_3 = 0 \quad (3)$$

where

$$P_1 = -2L_2L_4 \sin \theta_2 \quad (4)$$

$$P_2 = 2L_4(L_1 - L_2 \cos \theta_2) \quad (5)$$

$$P_3 = L_1^2 + L_2^2 - L_3^2 + L_4^2 - 2L_1L_2 \cos \theta_2 \quad (6)$$

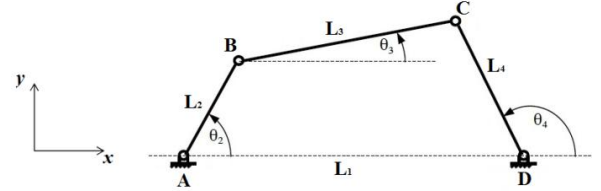


Figure 1: Four-Bar Linkage Mechanism

After some trigonometric manipulation operations and variable changing, θ_3 and θ_4 can be defined as a function of θ_2 [15]

$$\theta_4 = 2 \tan^{-1} \left(\frac{-P_1 \mp \sqrt{P_1^2 + P_2^2 - P_3^2}}{P_3 - P_2} \right) \quad (7)$$

$$\theta_3 = \tan^{-1} \left(\frac{-L_2 \sin \theta_2 + L_4 \sin \theta_4}{L_1 - L_2 \cos \theta_2 + L_4 \cos \theta_4} \right) \quad (8)$$

2.2. Equation of Motion of the Four-Bar Linkage

Equation of motion of the four-bar linkage mechanism has been obtained using Lagrange equation which can be defined as:

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{\eta}} - \frac{\partial L}{\partial \eta} = \delta W \quad (9)$$

where η is the generalized coordinate, L is the Lagrangian and W is the work done by external load. In the present study, external load has not been considered. Lagrangian can be written as:

$$L = T - U \quad (10)$$

where T and U are the total kinetic and potential energy of four-bar linkage. Total energies can be defined for each linkage member as:

$$T = \left(\frac{1}{2} m_2 V_2^2 + \frac{1}{2} I_2 \dot{\theta}_2^2 \right) + \left(\frac{1}{2} m_3 V_3^2 + \frac{1}{2} I_3 \dot{\theta}_3^2 \right) + \left(\frac{1}{2} m_4 V_4^2 + \frac{1}{2} I_4 \dot{\theta}_4^2 \right) \quad (11)$$

$$U = (m_2 g h_2) + (m_3 g h_3) + (m_4 g h_4) \quad (12)$$

Following parameters can be written:

$$V_2 = \frac{L_2}{2} \dot{\theta}_2, I_2 = \frac{1}{12} m_2 L_2^2, h_2 = \frac{L_2}{2} \sin \theta_2 \quad (13)$$

$$V_3 = \left| \frac{d}{dt} \left[\left(L_2 \cos \theta_2 + \frac{L_3}{2} \cos \theta_3 \right) + \left(L_2 \sin \theta_2 + \frac{L_3}{2} \sin \theta_3 \right) \right] \right|, I_3 = \frac{1}{12} m_3 L_3^2, h_3 = L_4 \sin \theta_4 - \frac{L_3}{2} \sin \theta_3 \quad (14)$$

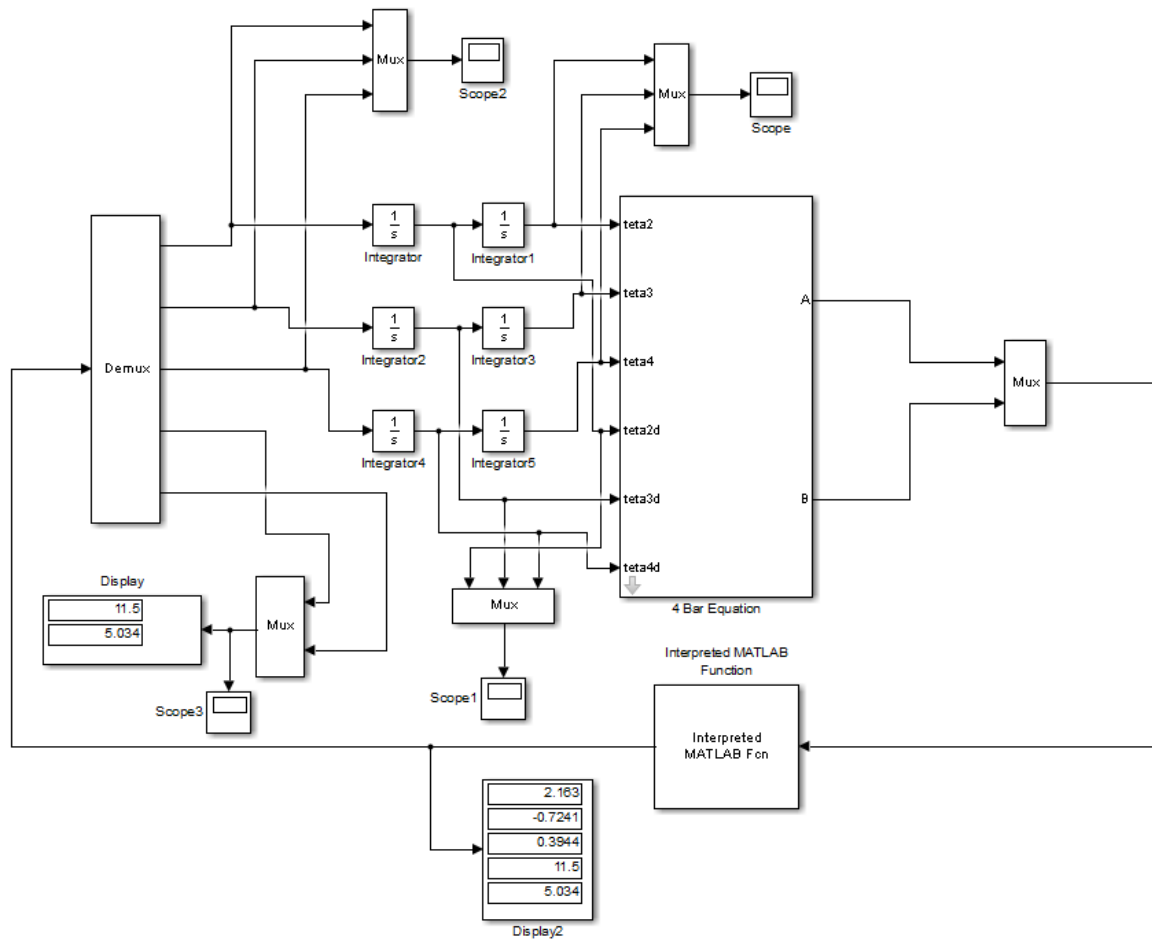


Figure 2: Simulink Block Diagram of Governing Equation of Four-Bar Linkage Mechanism

Table 1: Assumed Four-Bar Linkage Dimensions and Initial Conditions

Link Lengths (m)	$L_1=3$, $L_2=1$, $L_3=4$, $L_4=2.5$
Link masses (kg)	$m_1=1$, $m_2=1$, $m_3=1$
Initial angular positions (degree); Case 1	$\theta_2=30^\circ$, $\theta_3=20.71^\circ$, $\theta_4=49.98^\circ$
Initial angular positions (degree); Case 2	$\theta_2=60^\circ$, $\theta_3=18.58^\circ$, $\theta_4=58.89^\circ$

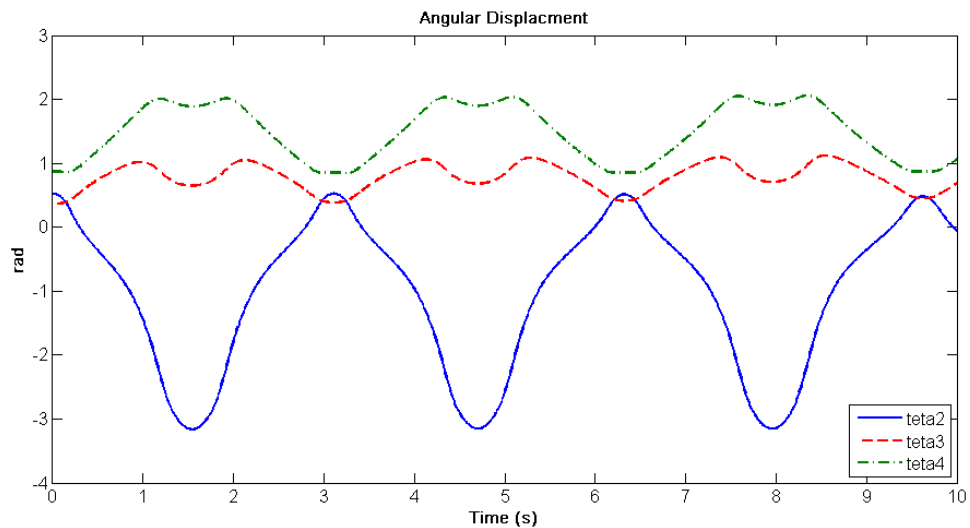


Figure 3: Variation of Angular Displacements with Time

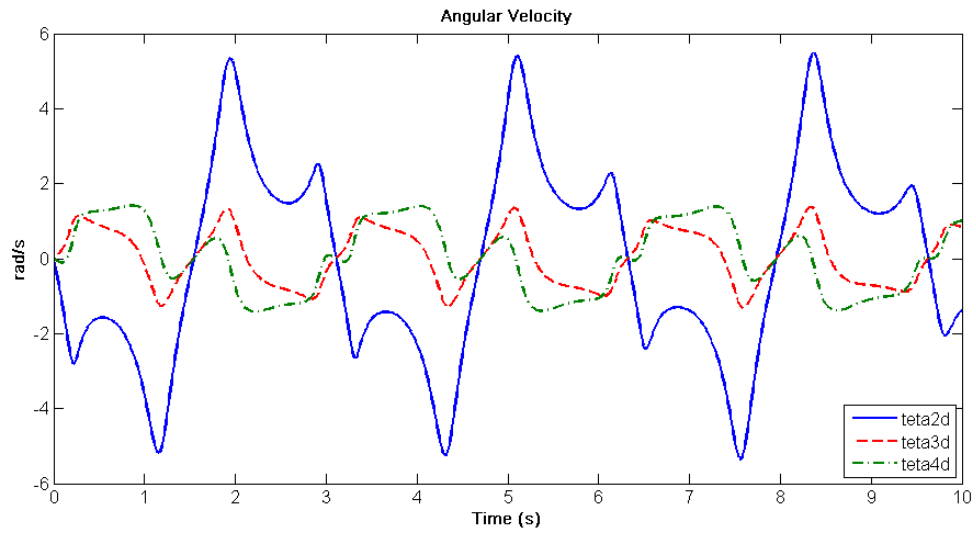


Figure 4: Variation of Angular Velocity with Time

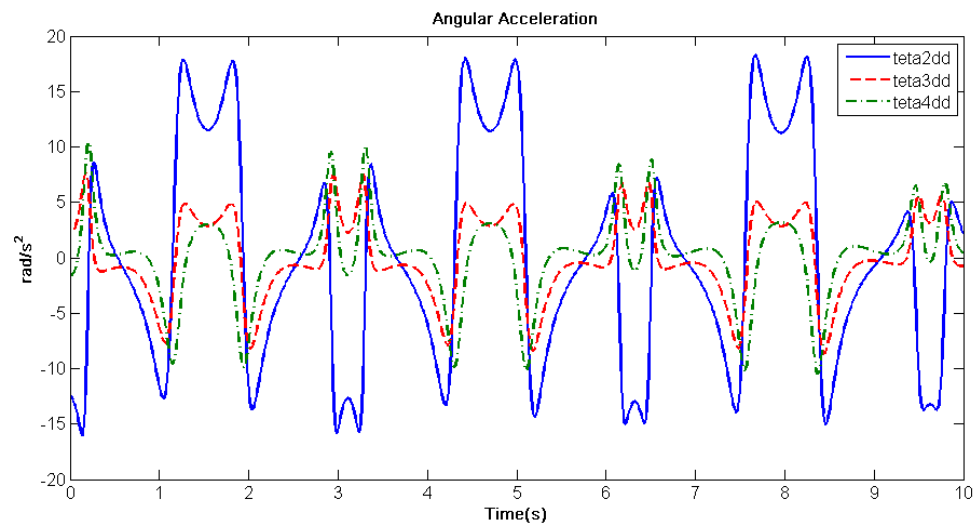


Figure 5: Variation of Angular Acceleration with Time

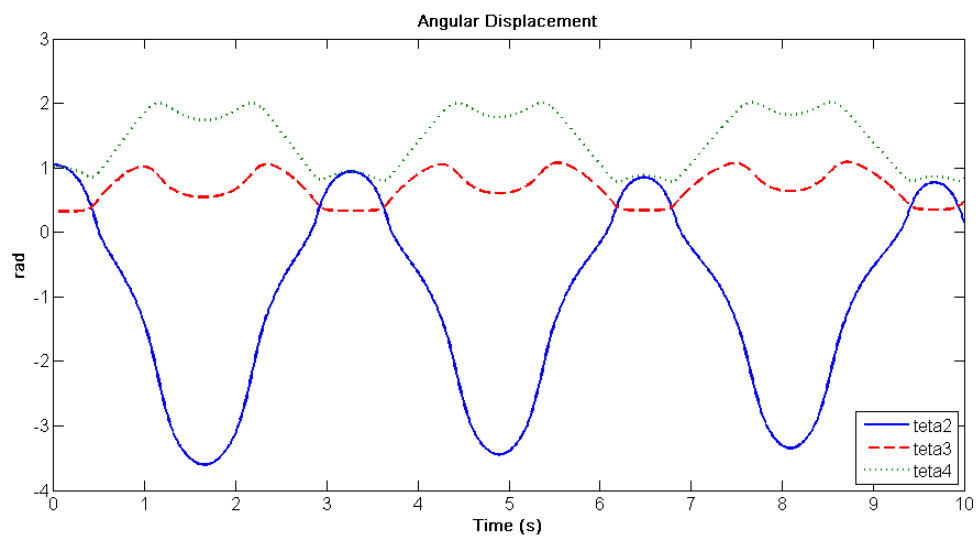


Figure 1: Variation of Angular Displacements with Time

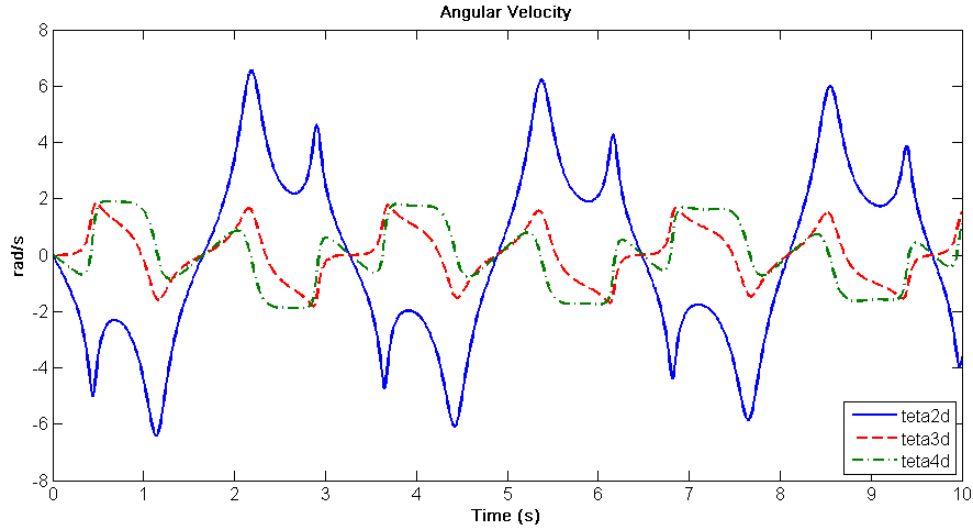


Fig. 2: Variation of Angular Velocity with Time

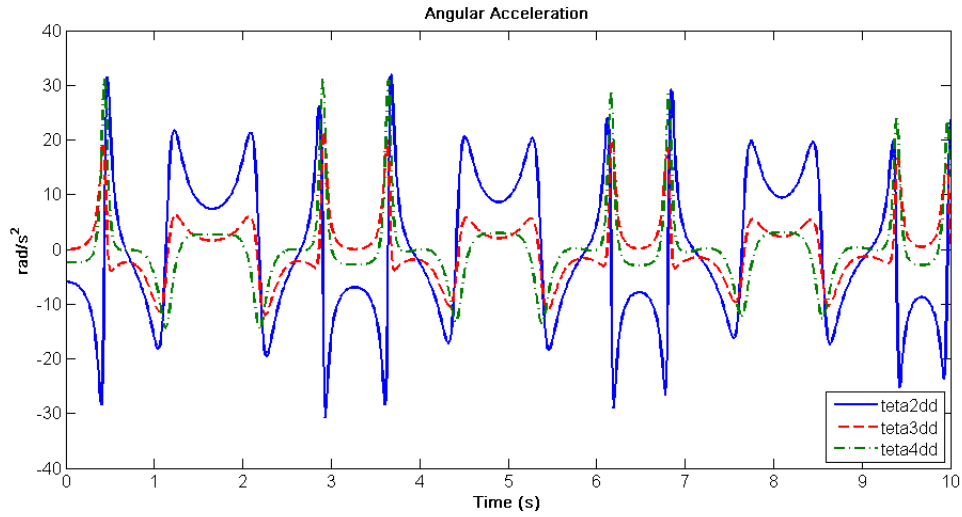


Figure 3: Variation of Angular Displacements with Time

$$V_4 = \frac{L_4}{2} \dot{\theta}_4, I_4 = \frac{1}{12} m_4 L_4^2, h_4 = \frac{L_4}{2} \sin \theta_4 \quad (15)$$

Nonlinear systems of equations for four-bar linkage consist of 5 equations: They are Langrange functions for each angular displacement and two geometric constraint function. Constraint functions are defined as:

$$\alpha_1 = L_2 \cos \theta_2 + L_3 \cos \theta_3 - L_4 \cos \theta_4 - L_1 \quad (16)$$

$$\alpha_2 = L_2 \sin \theta_2 + L_3 \sin \theta_3 - L_4 \sin \theta_4 \quad (17)$$

Langrange function for θ_2 :

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{\theta}_2} - \frac{\partial L}{\partial \theta_2} = \lambda_1 \frac{\partial \alpha_1}{\partial \theta_2} + \lambda_2 \frac{\partial \alpha_2}{\partial \theta_2} \quad (18)$$

where λ_1 and λ_2 are the Lagrange coefficients. If Eq. (18) is reorganized after necessary derivations, Eq. (19) can be obtained:

$$\begin{aligned} & \ddot{\theta}_2 \left[\frac{1}{3} m_2 L_2^2 + m_3 L_2^2 \right] + \ddot{\theta}_3 \left[\frac{1}{2} m_3 L_2 L_3 \cos(\theta_2 - \theta_3) \right] + \\ & \lambda_1 [L_2 \sin \theta_2] + \lambda_2 [-L_2 \cos \theta_2] = -\frac{1}{2} m_3 L_2 L_3 \dot{\theta}_3^2 \sin(\theta_2 - \theta_3) - \\ & m_2 g \frac{L_2}{2} \cos \theta_2 \end{aligned} \quad (19)$$

Langrange function for θ_3 :

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{\theta}_3} - \frac{\partial L}{\partial \theta_3} = \lambda_1 \frac{\partial \alpha_1}{\partial \theta_3} + \lambda_2 \frac{\partial \alpha_2}{\partial \theta_3} \quad (20)$$

$$\begin{aligned} & \ddot{\theta}_2 \left[\frac{1}{2} m_3 L_2 L_3 \cos(\theta_2 - \theta_3) \right] + \ddot{\theta}_3 \left[\frac{1}{3} m_3 L_3^2 \right] + \lambda_1 [L_3 \sin \theta_3] + \\ & \lambda_2 [-L_3 \cos \theta_3] = \frac{1}{2} m_3 L_2 L_3 \dot{\theta}_2^2 \sin(\theta_2 - \theta_3) + m_3 g \frac{L_3}{2} \cos \theta_3 \end{aligned} \quad (21)$$

Langrange function for θ_4 :

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{\theta}_4} - \frac{\partial L}{\partial \theta_4} = \lambda_1 \frac{\partial \alpha_1}{\partial \theta_4} + \lambda_2 \frac{\partial \alpha_2}{\partial \theta_4} \quad (22)$$

$$\ddot{\theta}_4 \left[\frac{1}{3} m_4 L_4^2 \right] + \lambda_1 [-L_4 \sin \theta_4] + \lambda_2 [L_4 \cos \theta_4] = -\left(m_3 + \frac{m_4}{2} \right) g L_4 \cos \theta_4 \quad (23)$$

Also, second time derivatives of geometric boundary conditions will take place in the governing equation of four-bar linkage:

$$\begin{aligned} & \ddot{\theta}_2 [L_2 \sin \theta_2] + \ddot{\theta}_3 [L_3 \sin \theta_3] + \ddot{\theta}_4 [-L_4 \sin \theta_4] = \\ & -L_2 \dot{\theta}_2^2 \cos \theta_2 - L_3 \dot{\theta}_3^2 \cos \theta_3 + L_4 \dot{\theta}_4^2 \cos \theta_4 \end{aligned} \quad (24)$$

$$\begin{aligned} & \ddot{\theta}_2 [L_2 \cos \theta_2] + \ddot{\theta}_3 [L_3 \cos \theta_3] + \ddot{\theta}_4 [-L_4 \cos \theta_4] = \\ & L_2 \dot{\theta}_2^2 \sin \theta_2 + L_3 \dot{\theta}_3^2 \sin \theta_3 - L_4 \dot{\theta}_4^2 \sin \theta_4 \end{aligned} \quad (25)$$

These equations can be reorganized in a matrix form:

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} & A_{15} \\ A_{21} & A_{22} & A_{23} & A_{24} & A_{25} \\ A_{31} & A_{32} & A_{33} & A_{34} & A_{35} \\ A_{41} & A_{42} & A_{43} & A_{44} & A_{45} \\ A_{51} & A_{52} & A_{53} & A_{54} & A_{55} \end{bmatrix} \begin{bmatrix} \ddot{\theta}_2 \\ \ddot{\theta}_3 \\ \ddot{\theta}_4 \\ \lambda_1 \\ \lambda_2 \end{bmatrix} = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} \quad (26)$$

where related parameters can be defined as:

$$A_{11} = \frac{1}{3}m_2L_2^2 + m_3L_2^2, A_{12} = \frac{1}{2}m_3L_2L_3 \cos(\theta_2 - \theta_3), A_{13} = 0, A_{14} = L_2 \sin \theta_2, A_{15} = -L_2 \cos \theta_2 \quad (27)$$

$$A_{21} = \frac{1}{2}m_3L_2L_3 \cos(\theta_2 - \theta_3), A_{22} = \frac{1}{3}m_3L_3^2, A_{23} = 0, A_{24} = L_3 \sin \theta_3, A_{25} = -L_3 \cos \theta_3 \quad (28)$$

$$A_{31} = 0, A_{32} = 0, A_{33} = \frac{1}{3}m_4L_4^2, A_{34} = -L_4 \sin \theta_4, A_{35} = L_4 \cos \theta_4 \quad (29)$$

$$A_{41} = L_2 \sin \theta_2, A_{42} = L_3 \sin \theta_3, A_{43} = -L_4 \sin \theta_4, A_{44} = 0, A_{45} = 0 \quad (30)$$

$$A_{51} = L_2 \cos \theta_2, A_{52} = L_3 \cos \theta_3, A_{53} = -L_4 \cos \theta_4, A_{54} = 0, A_{55} = 0 \quad (31)$$

$$B_1 = -\frac{1}{2}m_3L_2L_3\dot{\theta}_3^2 \sin(\theta_2 - \theta_3) - m_2g\frac{L_2}{2} \cos \theta_2 \quad (32)$$

$$B_2 = \frac{1}{2}m_3L_2L_3\dot{\theta}_2^2 \sin(\theta_2 - \theta_3) + m_3g\frac{L_3}{2} \cos \theta_3 \quad (33)$$

$$B_3 = -\left(m_3 + \frac{m_4}{2}\right)gL_4 \cos \theta_4 \quad (34)$$

$$B_4 = -L_2\dot{\theta}_2^2 \cos \theta_2 - L_3\dot{\theta}_3^2 \cos \theta_3 + L_4\dot{\theta}_4^2 \cos \theta_4 \quad (35)$$

$$B_5 = L_2\dot{\theta}_2^2 \sin \theta_2 + L_3\dot{\theta}_3^2 \sin \theta_3 - L_4\dot{\theta}_4^2 \sin \theta_4 \quad (36)$$

Nonlinear system of equations in Eq. (26) has been solved with MATLAB and discretization and derivation process are carried out by Simulink program. In Fig. (2), Simulink model for present problem is given.

3. Simulation Results

Simulation of the four-bar linkage mechanism is carried out by using Simulink. Simulation time is accepted as 10s. "ode45" solver has been used and sample time assumed as 0.01s. Four-bar linkage mechanism dimensions were taken from Ref. [14] as in Table (1). Two different initial conditions for linkage's angular position have been considered. Only inertial forces on four-bar mechanism were assumed. External load has not been considered. Simulation results can be seen in Figs (3)-(5) for 1st case study and Figs (6)-(8) for 2nd case study.

Periodic dynamic behavior of four-bar linkage can be seen in figures. Changing of initial position conditions, occurs a phase-shifting in dynamic behavior of four-bar linkage mechanism. Also angular variable amplitudes increases in 2nd case study and this effect can be seen clearly changing of angular acceleration (See Figs. (5) and (8)).

4. Conclusion

Dynamic analysis of four-bar linkage mechanism has been studied in the present study. Equation of motion for each linkage part was obtained using Langrange formulation. Discretization and solution process of nonlinear differential equations are carried out by using Simulink and MATLAB, respectively. Only inertial effect on dynamics on the four-bar linkage was considered.

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Effect of Weight and Diameter Variables on Balance Process for Inertia Wheel Pendulum by Using Swing Up and PID Controller

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Abstract: Inertia wheel pendulum balance control is performed by using swing up and PID controller with different wheel weight and diameters. In the pendulum control, 3 different radius wheels and different weights are added to analyze whether the system remained balance position. In this process, the effect of weight and diameter variables on the swing time and PID coefficients of the pendulum was observed. With this observation, the effects of input variables in the real-time system were compared with calculations in the dynamic pendulum model.

KEYWORDS: WHEEL PENDULUM, PID CONTROLLER, SWING UP CONTROLLER

1. Introduction

Inertia wheel pendulum (IWP) is a nonlinear and underactuated system with two degrees of freedom. The pendulum structure consists of a pendulum rod that can swing freely in the vertical axis, a rotating wheel in the same axis with the rod, and a motor that produces a rotational movement[1]. The main purpose of the IWP systems is the alignment of the pendulum wheel on the vertical axis. Balancing is the process of raising and aligning the pendulum with the control methods of the torque produced by the DC motor[2].

The aim of this study is to control the alignment of the pendulum wheel in different weights and diameters. In most of the studies about IWP, different control methods and different mechanical design have been applied on a single wheel. In this study, comparison of the factors affecting the balance position was made, unlike other designs. In the balancing process, 39 different experiments were conducted and balance condition was analyzed together with friction, engine heating and other disturbing factors affecting the system. As a result of this comparison, observation is included, except for mathematical dynamic calculations.

Rest of the information of this document is organized as follows: Sec. 2 is devoted to describing the IWP system control method. Sec. 3 indicates the results and discussion. In Sec 4. Conclusion, data analysis of wheel balance.

2. System Control Method

Different control methods are used at various stages in order to realize the movement of the pendulum from 0 degrees to 180 degrees with the least energy consumption[3],[4],[5],[6]. In the design of the pendulum, the movement is provided by Dc motor with control signals generated by the Arduino control card as shown in the figure 1 block diagram. During the swing process, the angle and position information are measured by the encoder and conveyed to the control unit for feedback. In this study, two different methods is used as shown in the flow diagram in figure 2. The first is the swing up control of the pendulum and the second is the balance control of the pendulum with PID.

2.1. Swing Up Control

The Swing Up control does not balance the pendulum to the desired vertical alignment but supports it to arrive in the angular range where the balance will take place.[4] The position of the pendulum wheel is 0° at the beginning. The ramp function or any triggering is applied to start the wheel swinging in figure 3. As a result of the trigger, the wheel starts to swinging clockwise and counterclockwise. The swinging should be supported to increase the pendulum from 0° to 180° degrees. This support is applied with the

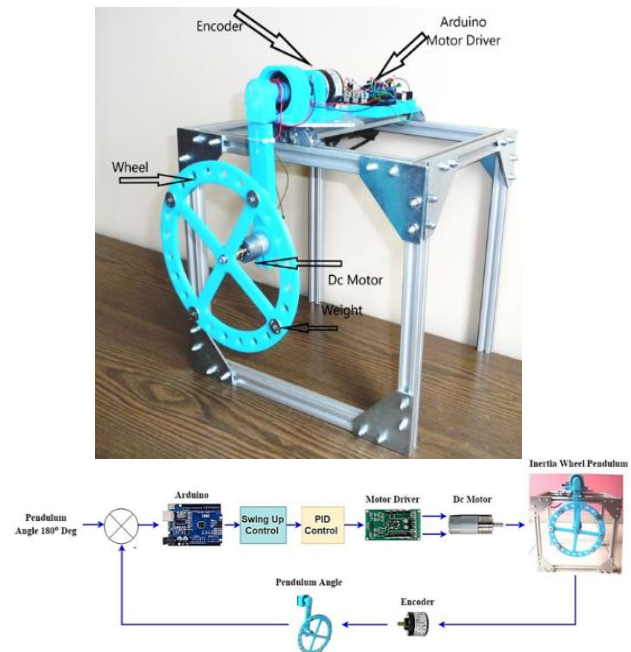


Fig. 1. Wheel pendulum mechanism and control block diagram

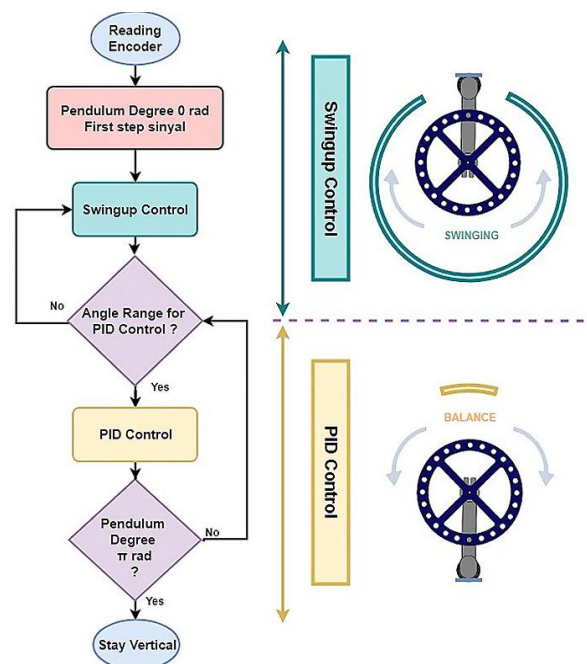


Fig. 2. Control flow diagram

torque produced by the dc motor. The support torque is applied when the variable pendulum angle value is maximum and the acceleration is zero during the swinging process. As a result of these processes, the pendulum is increased to the desired swinging range. The pendulum control process switches to the balance control range when the swinging operation is complete[7].

2.2. PID Controller

Proportional-integral-derivative (PID) controllers are the most important control systems used to control processes, due to their simple and easy design, low cost and wide range of applications [8]. The main purpose of the PID control system is that the controlled process variable reaches the target in minimum time with error difference shown in figure 5. PID control compares the reference value and feedback variables. In order to eliminate the error between two variables, proportional, integral and derivative parameters are

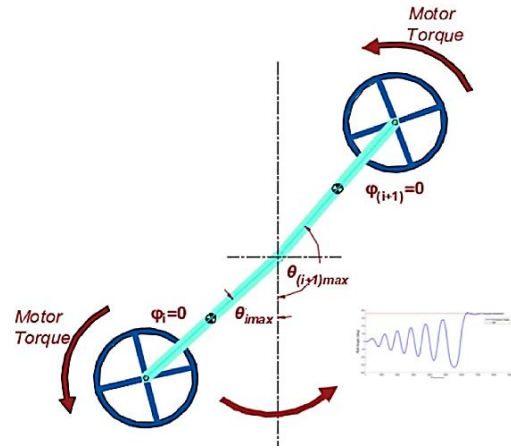
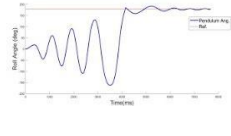
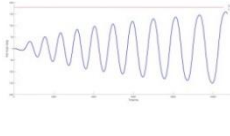
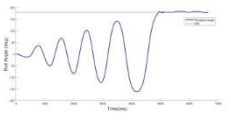
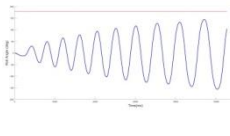
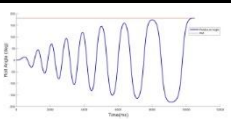
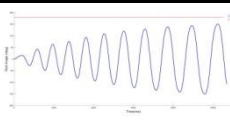
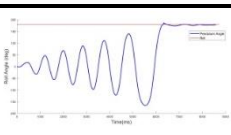
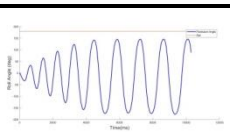
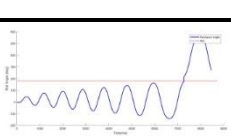
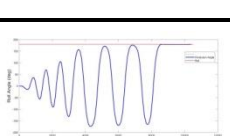
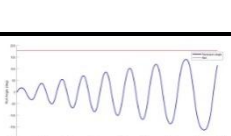
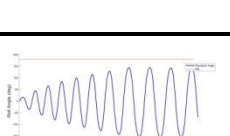
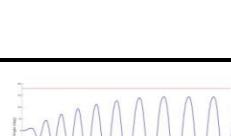
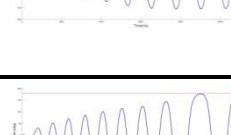
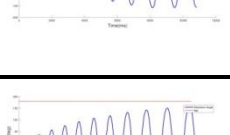


Fig. 3. Initial swing up control

Table 1: Sample of the experiment data of the wheel characteristic list, swing count and balance position.

Wheel Radius-Weight	Pendulum Angle-Time Graph	Swing-count	Wheel Radius-Weight	Pendulum Angle-Time Graph	Swing-count
		Balance			Balance
R9-90gr		5	R7.5-165gr		10
		Balance			No Balance
R9-144gr		5	R7.5-185gr		9
		Balance			No Balance
R9-171gr		8	R7.5-225gr		9
		Balance			No Balance
R9-220gr		7	R6-73gr		7
		Balance			No Balance
R9-240gr		8	R6-100gr		8
		No Balance			Balance
R9-283gr		7	R6-127gr		9
		No Balance			No Balance
7.5-85gr		7	R6-154gr		10
		No Balance			No Balance
R7.5-115gr		10	R6-182gr		10
		Balance			No Balance

applied to the system. These parameters modify according to the system model. These Parameters are used in continuous cycling method and system response methods developed by Ziegler-Nichols. Large settling time and overshoot are minimized by Kp Ki Kd parameters[9],[10].

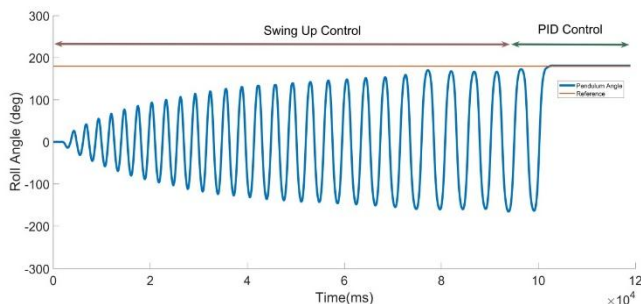


Fig. 4. Pendulum control angle-time graph

Figure 4 shows the oscillation and position information of the pendulum during the swing up and PID control processes. The pendulum wheel lasted approximately 2 minutes from 0° to 180°. The majority of this period time was in the swing up control. The PID control process is activated when the value of the pendulum angle between 170° and 190°.

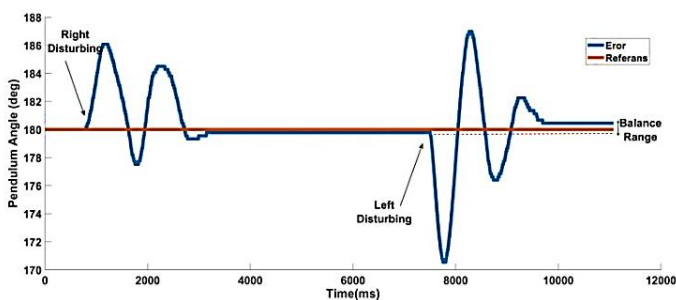


Fig. 5. Balance disturbing impact graph

In the curves seen in figure 5, the imbalance caused by the right and left disturbing effects applied to the pendulum wheel appears. This imbalance is corrected by the torque generated by the dc motor. Dc motor control was done with PID with Arduino Uno microcontroller.

3. Results and Discussion on Experiment

In the table 1 show that, the balance of the wheel of different weights and diameters and the number of oscillations. The 16 data in this table are selected as examples. This information gives us an idea of which pendulum wheel to choose according to the design of the experimental setup. Wheel selection can also be calculated according to the dynamic model of IWP, but when it is included in real-time control in disturbing factors, there are differences between the model result and the application result.

4. Conclusion

In this study, a control of nonlinear and underactuated system was achieved by swing up control and PID control at various angle stages. The most significant factors affecting the stability of IWP systems are wheel diameter and wheel weight. These inputs were applied to the IWP system with different values.

In the swing up control process, as it appears in the results in table 1, it was observed that the weight supported to balance position

until the to an amount. In case the pendulum weight is light or too heavy, the balancing operation was not realized. As the wheel radius expands, the pendulum was more easily balanced with lighter weight in the process.

When the PID control process was examined, it was found that heavy loads and small diameter wheels were better balanced angularly on the vertical axis in the range of 90°+-2°, but balance control became difficult as the wheel diameter increased. Pendulum range between of the 85°-88° and 92°-95° for PID balance control bigger wheel radius and light wheel make it more can be tolerated.

As a result of this study, the system input factors affecting the balance processes of IWP systems were analyzed and as a result, it was found that wheels with large, light and high moments of inertia were better in the balancing process.

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Analysis of welding of aluminium alloy AA6082-T6 by TIG, MIG and FSW processes from technological and economic aspect

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Abstract: Welding is a manufacturing process, which uses heat or pressure to form a homogeneous weld when joining homogeneous or heterogeneous metal materials or thermoplastics. The last decade has been characterized by the intensive development of unconventional welding processes, which use friction as an energy source, and in developed countries have taken primacy over conventional welding processes. The modern welding process, known as Friction Stir Welding (FSW), offers many advantages over conventional Tungsten Inert Gas (TIG) and Metal Inert Gas (MIG) processes, both in terms of weld quality and environmental protection and in terms of saving time and materials needed to perform quality welding. This paper presents TIG, MIG and FSW welding technologies, with all the advantages and disadvantages, and the possibilities of their application in welding AA6082-T6 aluminum alloy (6xxx series), characterized by medium strength and outstanding corrosion resistance.

Keywords: WELDING, TIG, MIG, FSW, COST

1. Introduction

Welding is a technological process that has a wide range of applications in the manufacture of metal products in the mechanical, automotive, aviation, construction and energy industries. During the period after the First World War, there was an intensive development of welding, so during that time portable welding machines were developed in the protective atmosphere of inert and active gas.

Nowadays, welding technology is at a highly advanced level, which makes it possible to use it in all conditions - in space, underwater, at high altitudes, etc., and precision machines have been constructed, which perform defined operations with lasers. Conventional welding processes, in developed industrial countries, are being replaced by new, unconventional ones, including Friction Stir Welding (FSW) or friction welding, patented in 1991 by The Welding Institute (TWI) in England. Originally, this welding process was intended solely for welding aluminum and its alloys [1].

FSW technology, in addition to its original use in aluminum welding, is now successfully used in welding copper, brass and various types of steel. In addition, the orbital variant of the FSW process is used for welding metal and plastic tubes, the spot welding is used in the automotive industry, and for complex shapes and contours, a robotic FSW procedure is in use [1].

The advantages of the FSW welding process over conventional technologies, primarily TIG and MIG, have been explained in the work of a number of researchers [2- 4]. The peculiarity of this process is reflected in the time and cost required to perform welding, and in the protection of health and the environment, as well as safety at work.

This paper analyzes the welding of aluminum alloy 6xxx series (AA6082-T6) from the aspect of three technological processes, namely two melting welding processes (TIG and MIG) and one non-melting process (FSW).

Welding aluminum is difficult for many reasons. Aluminum has a high thermal conductivity, a low melting point relative to the oxide layer, and an affinity for oxygen and hydrogen, which makes it difficult to weld.

Based on research based on a large number of literature sources, this paper wanted to point out the possibility of applying certain methods for welding aluminum, namely its alloy AA6082-T6.

2. Conventional welding processes

2.1. Tungsten Inert Gas (TIG)

TIG Technology, or Wolfram Inert Gas (WIG), or Gas Tungsten Arc Welding (GTAW) is arc welding with insoluble electrode in the protection of inert gas (argon, helium) or less often in a mixture of gases dominated by inert gas, whose original use binders for welding aluminum and its alloys thanks to the effect of cathodic cleaning [1, 5, 6].

Due to a number of advantages, this process is of use in welding a wide range of materials (steels, precious steels, heavy and light non-ferrous metals, etc.) in manual, semi-automatic or automatic applications. It found application in the automotive and aviation

industries, shipbuilding, production of transportation systems, various overhaul works, etc. The obtained compounds of high quality are the reason that the TIG process is currently irreplaceable in the design and installation of pipelines, boiler, petrochemical industry, etc. Good process mobility allows it to be applied in all spatial positions. Nowadays, characterized by a high degree of automation and application of modern technologies, the field of application of the TIG process is significantly expanded.

The main advantages of the TIG procedure are [5, 6]:

- high quality joint - faultless joint,
- no spattering - additional metal melts in the metal bath, does not transfer through the arc,
- excellent weld root control,
- precise control of welding parameters,
- good control of the heat source and the way of introducing additional material,
- no submerging,
- a large number of welding positions and
- possibility of welding of dissimilar metals.

In addition to a number of advantages, which are more dominant, the TIG process has its disadvantages, such as:

- relatively low welding speed and productivity,
- requires a high level of training of welders,
- inert gases are expensive, increasing the total cost of welding,
- in addition to the occurrence of defects in the weld due to inadequate welding techniques, as a result of the electrode overheating, tungsten particles may be introduced into the weld, thus reducing the quality of the weld,
- high cost of equipment and
- increase UV radiation.

2.2. Metal Inert Gas (MIG)

The MIG welding process represents arc welding with a full soluble wire electrode in the protection of inert gas or gas mixtures with a predominant argon or helium content.

This procedure is applicable for welding material 3-20 mm thick. In addition, pulsed MIG transmission is used for welding thin materials 1-4 mm thick, as well as for welding in forced positions [1].

The basic components that affect the electric arc that is created and therefore the metal transfer in the weld zone and the quality of the weld are the forces and chemical reactions that occur in the metal transfer area. The forces that occur and act in the zone of an arc are: electromagnetic force, gravity force, surface tension force of liquid metal, reaction force from the flow of steam from the surface of the melt and aerodynamic force [1].

The advantages of the MIG welding process are:

- high melting rate and high welding speed,
- applicable in forced positions,
- small investment costs (for the standard variant),
- excellent appearance of welded joints and
- easy process automation [6].

The disadvantages of the MIG welding process are:

- risk of welding errors,
- the risk of slow welding errors due to the leakage of liquid metal in front of the electric arc and
- relatively complicated welding training for high alloy steels and non-ferrous metals [6].

3. Friction stir welding (FSW)

In addition to aluminum and aluminum alloys, FSW is nowadays successfully used for welding bronzes, brass, as well as some types of steel. In addition, the orbital variant of the FSW procedure is used for welding metal and plastic tubes, the spot welding is applied in the car industry, and for complex shapes and contours, a robotic FSW procedure is in use [1].

The FSW procedure is performed in such a way that there are firmly clamped base plates on the machine table that need to be connected. A special cylindrical shape tool, consisting of two parts, the body and the working part of the tool, which rotate at high speed, is used to generate heat. The tool body is used to attach the tool to the clamping jaws of the machine, and the working part of the tool consists of two parts: a larger diameter called the shoulder and a smaller diameter part called the pin (Figure 1) [7].

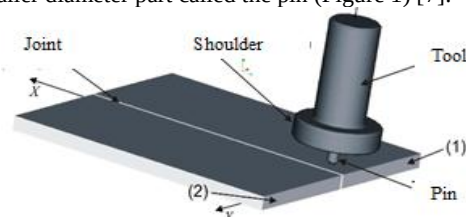


Figure 1. Tool and work pieces before welding [8]

The shape of the shoulder and the pin of the tool can have different structural geometric shapes. The shoulder of tool may have a concentric recess in its surface of usually semicircular shape, while the pin is usually conical, which can also be profiled by different coil shapes or different types of grooves. The height of the grooves mainly depends on the thickness of the welding (joining) sheets, but it is very important that it be a few millimeters smaller than the thickness of the sheet [8].

The FSW process starts with the positioning of the tool above the workbench of the machine, and its axis is normal to the touching line of the base plates. The rotary tool approaches the joint line slightly and plunges into the material - the base plates. On this occasion, heat is generated in the material and an initial hole is formed. The tool pin is plunged in the material until the tool face makes contact with the upper surface of the work pieces. The tool must with sufficient pressure hold the material within the weld zone and create a sufficient temperature for the FSW process to proceed smoothly [8]. The baseplate material is heated to near the melting point (~ 95%) and becomes plastic. With the help of a pin tool, such material flows around the sleeve and thus mixes. At the moment when the tool head touches the upper surfaces of the base plates, the axial movement of the tool is interrupted and the longitudinal movement of the stand begins. In further work, the tool pin practically slides between the sheets in the welding direction, the new material warms up, becomes plastic and is constantly mixed. During this time, a groove of smooth warmed material is formed behind the tool head, which cools and solidifies, and a monolithic joint is formed between the plates. In doing so, the tool face forms a flat seam surface on the top of the sheet, and on the underside, the base forms the same. The welding process is terminated by interrupting the translational movement of the tool and pulling it out of the weld zone axially upwards [8].

The thickness of the aluminum sheet that can be welded by this method depends on the strength of the machine and ranges from 0.5 mm to 50 mm in a single pass or single sided seam. It is possible to weld sheets up to 75 mm thick in double sided seam.

As the nature of FSW is a solid state, this gives it several advantages over metal melting welding methods: liquid phase cooling is avoided so that porosity (cavity), solution redistribution, and cracks formed by melting and solidification do not exist.

In principle, the FSW process has found great application. There are a number of disadvantages and as a process it is very tolerant in terms of variation of parameters and materials. One of the significant advantages over arc welding processes is that there is no distortion, ie. of sheet metal bending during the process itself, because the residual stresses are negligibly small.

In addition to the above, the FSW process has properties that are very rarely present in other processes: the formation of a welded joint with negligible internal stresses, resistant to corrosion, in materials for which this was not possible or extremely difficult and expensive to achieve by conventional methods welding. Due to all of the above, it can be said that, economically, FSW process is by far the most efficient and ecologically clean [8].

4. Aluminium alloy AA6082-T6

Aluminum and its alloys, as structural materials, characterized by good mechanical properties, corrosion resistance and relatively low mass, today occupy a significant place in almost all branches of industry. The most common use of aluminum alloy is in the shipbuilding, aerospace, aerospace, healthcare, construction, and other industries [9, 10].

Welding of aluminum and aluminum alloys is accompanied by certain technical problems that can be avoided by properly selecting the welding process and the additional material [9]. Aluminum oxide formed on the surface of the metal provides corrosion resistance, so subsequent surface protection is basically unnecessary. If the coating is removed, in contact with oxygen from the air it regenerates at that point. As Al oxide has a melting point of about 2050 °C and aluminum of about 660 °C, in the welding preparation process, this oxide must be removed mechanically from the junction site.

A special type of aluminum alloy from the 6xxx series (magnesium and silicon alloying elements), of which considerable attention will be paid in the next part, is the AA6082-T6 alloy. The T6 designation itself indicates that the AA6082 alloy has been further processed (T6 - heat treated in 580 °C and aged artificially at 180 °C, tensile strength of 340 MPa, 95 HB hardness and specific mass) to improve mechanical properties [11-13]. The alloy is a medium strength alloy with a high degree of corrosion resistance. If the whole 6xxx series is considered, then this alloy has the highest strength, so it is not infrequently used as a replacement for some alloys in this series, especially for the construction of high load structures and the like [12].

The chemical composition of AA6082-T6 alloy is shown in Table 1 [7].

Table 1. Chemical composition of AA6082-T6 alloy

Al	Fe	Si	Ti	Cu	Zn	V	Cr	Mn	Mg	Na
%	%	%	%	%	%	%	%	%	%	%
98.25	0.22	0.85	0.01	0.002	0.062	0.006	0.001	0.16	0.43	0.002

5. Comparison of welding of AA6082-T6 alloy from the aspect of manufacturability by TIG, MIG and FSW processes

In the next part of this paper, attention will be paid to the welding technology of said alloy, TIG, MIG and FSW processes, and an advanced analysis of these procedures will be made. Comparisons between the selected procedures to be analyzed are: time and cost of preparation of welding joint, cost of additional material, cost of protective atmosphere, energy consumption during welding, welding time and possible spatial positions of welding.

The comparison was considered when welding the face joint of the plates, AA6082-T6 alloy, length 1 m and thickness 6 mm. The consideration will take into account that the panels have been adequately machined to a defined length and width, and the time and cost of these panel preparations will not be taken into account.

5.1. Time and cost of preparing the weld joint

A special feature and problem in welding aluminum and its alloys is the oxide layer (Al_2O_3), which is constantly formed on the

surface of the alloy and its high melting point relative to the low aluminum melting temperature. Aluminum oxide represents a basic difficulty that must be overcome in the arc welding of aluminum and aluminum alloys [14, 15], so it is necessary to remove the oxide layer from the base material. In the case of arc jointing of the material, especially in the formation of an interface, the groove side. The preparation of the groove sides of the TIG and MIG procedures for the AA6082-T6 aluminum alloy, $s = 6$ mm thick, is shown in Figure 2.

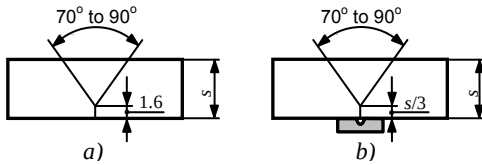


Figure 2. Preparation of weld seams: a) with TIG procedure for material of thickness 6 mm; b) in the MIG process for a material thickness of ≈ 6 mm [16]

Considering that the cutting of the edges is performed by a spindle milling machine, and that the time required to perform this operation is calculated by the form:

$$t_t = t_p + t_m \quad (1)$$

where are:

t_t - total time (min) required to cut the edge,

t_p - preparation time, which refers to the preparation of the machine, tools, positioning of objects, program entry and the like, and is about 30-40 min,

t_m - main process time (min).

According to the calculation, the time required for the preparation of the arc welding plates is 50-60 min, and the cost of preparing them is approximately 20 €.

In addition to the above costs, unlike the MIG process, the costs associated with preheating the material prior to the welding process must be added to the TIG process. In this regard, the preparation time for the TIG process is significantly higher than for the MIG process, because the heating of the AA6082-T6 alloy is performed at 200 °C for 30 min [17].

Unlike the aforementioned procedures, in the FSW process, the numerous costs of preparing the material are minimized, to be exact, almost nonexistent. In this process it is not necessary to preheat the material or to remove the protective oxide layer from the alloy surface in order to perform this process.

The time and cost required to prepare the material are shown in the diagrams in Figure 3 and Figure 4.

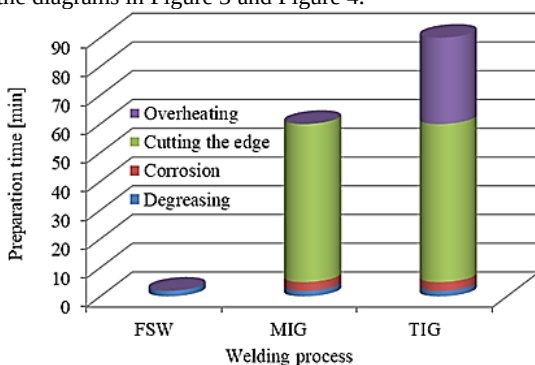


Figure 3. Preparation time of material AA6082-T6 of thickness 6 mm for FSW, MIG and TIG welding

5.2. Cost of additional material

Material that is added or introduced into the welding zone during the welding process and which together with the base material participates in the formation of the weld is called additional material. In general, 6xxx series alloys are not recommended to be welded without additional material, or to use additional material the same as the base material as cracking may occur in the weld [18].

Performing the TIG procedure is possible with or without additional material, that is, if the thickness of the base material is less than 3 mm, additional material is not required, otherwise it is necessary [5].

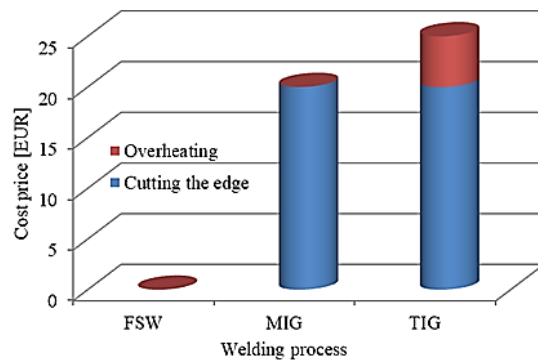


Figure 4. Costs of material preparation AA6082-T6 of thickness 6 mm for FSW, MIG and TIG welding

According to the literature source [19], additional material ER4043 is used when welding the AA6082-T6 TIG alloy process.

The speed of introduction of the auxiliary material and its diameter should be consistent with the welding speed and represent one of the main welding parameters, and are selected based on the thickness and type of the base material, as well as the welding position [9].

It is important to note that during the FSW welding process, no additional material is introduced into the process, the welding is performed without additional material.

Based on the recommendation of literature sources [20-23], the consumption of additional material for welding 1 m of AA6082-T6 of thickness 6 mm alloy was calculated and the calculated values are shown in the diagram in Figure 5.

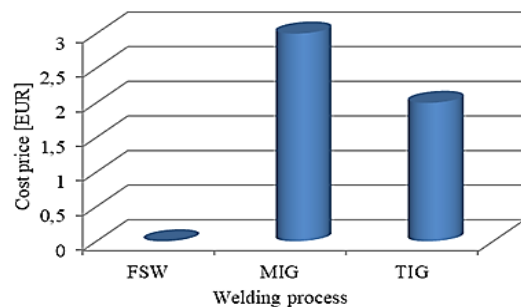


Figure 5. Costs of additional material required for welding AA6082-T6 of thickness 6 mm FSW, MIG and TIG

5.3. Time of welding

Welding time is another of the technological parameters when comparing TIG, MIG and FSW procedures.

When calculating the welding time, it is necessary to pay attention to the number of passes required to obtain the weld, and in this connection TIG and MIG welding of AA6082-T6 alloy of thickness 6 mm is performed in two, while FSW welding is performed in one pass.

Considering the researches [20, 22, 24], the time required for welding of AA6082-T6 alloy plates, length 1 m and of thickness 6 mm, by TIG, MIG and FSW procedures was calculated and is shown in the diagram in Figure 6, while the total time required to perform of these procedures is illustrated by the diagram in Figure 7.

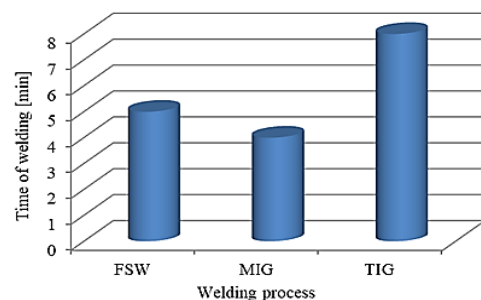


Figure 6. Time for welding by TIG, MIG and FSW processes

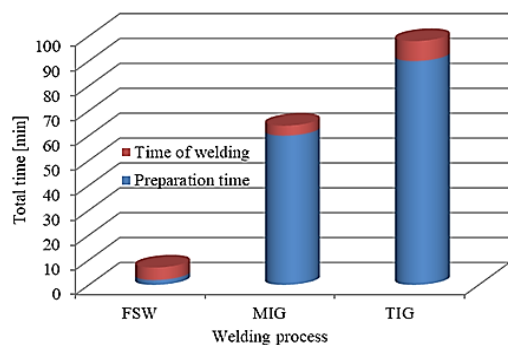


Figure 7. Total time of extraction FSW, MIG and TIG processes

5.4. Cost of a protective atmosphere

The cost of a protective atmosphere is another indication of the advantages of the FSW procedure over the TIG and MIG procedures. In fact, FSW welding does not require a protective atmosphere, while in TIG and MIG procedures it is necessary.

Based on the research [20, 22, 25], the argon consumption during welding of AA6082-T6 alloy, 1 m and of thickness 6 mm in length, was calculated by TIG and MIG procedures and presented, together with other costs, in Figure 8.

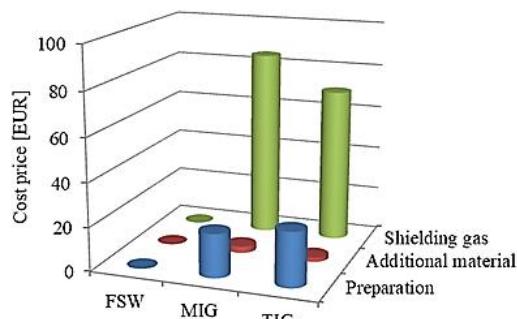


Figure 8. Individual costs of welding processes

5.5. Amount of heat input

A factor that greatly influences the shape and dimensions of weld metal and welds as a whole, the micro and macrostructure of weld metal and its properties, the occurrence of defects in the welded joint and the appearance of residual stresses is the energy that is brought under the influence of an electric arc welded joint [26].

The amount of energy input is a fraction of the total energy of the arc that is spent on forming a unit of length of weld. The amount of energy input is determined from the expression [26]:

$$Q = \frac{k \cdot U \cdot I}{v} \quad (\text{J/m}) \quad (2)$$

where are:

k - coefficient of thermal efficiency (for TIG - 0.6, and for MIG - 0.8),

U - voltage (V),

I - amperage (A) and

v - welding speed (m/s).

Unlike the TIG and MIG procedures, in the FSW process, the amount of energy input cannot be calculated using the form provided. However, based on data from a literature source [27], related to the amount of energy input in the FSW process, and based on the calculation by equation (2) for the TIG and MIG procedures, the amount of energy input for the individual welding operations is shown in the diagram in Figure 9.

6. Conclusion

Considering the time aspect of the overall process execution, including the time required to prepare the base material for welding and welding time, the FSW process takes precedence. In fact, in this process, preparation of the material is not required, while in the other two processes it is necessary, especially in the TIG process,

which in addition to mechanical preparation of the material also requires its preheating. Therefore, the longest time is required for TIG welding and the shortest time for FSW welding.

However, if an economic analysis of the process, which includes material preparation costs, additional material costs and protective gas costs, is taken into account, FSW procedure is again preferred because material preparation costs are not present, no additional material is required, as well as protective gas. Most costs occur with MIG welding due to the high consumption of shielding gas.

Comparing the values related to the total amount of heat input during welding, it is concluded that from the energy point of view, FSW is a cost-effective procedure and is favored over the other two processes.

In addition to all of the above, today, which is characterized by high levels of pollution, great attention should be paid to the protection of the environment. From this point of view, the FSW process is one of the environmental practices because there is no evaporation of harmful gases, no protective gas required, high energy savings, etc.

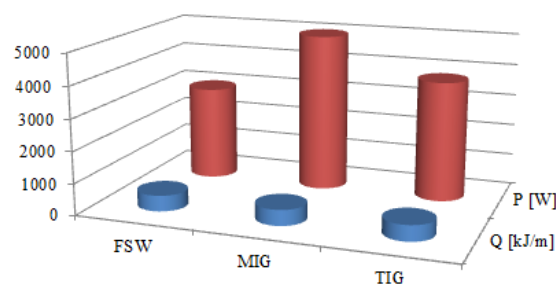


Figure 9. Quantity of heat input and power consumption

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Determination of the parameters of the drying process of sodium bicarbonate in a pneumatic dryer

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Abstract: This paper describes the process of drying baking soda in a pneumatic dryer. A description of a drying plant with honeycomb elements is provided. Due to the extensive work, only one part of the results of the study is presented, which is related to the material-energy balance, the calculation of the final humidity, the change of the air condition (humidity and temperature) in the bicarbonate drying process. Part of the research results related to the application of I-X - diagram in the drying process of NaHCO_3 is presented.

Keywords: PNEUMATIC DRYER, SODIUM BICARBONATE, TEMPERATURE, HUMIDITY, HEAT TRANSFER

1. Introduction

The drying of the material or of a product is accomplished by different processes, depending on the purpose, further use, and the need to process the dried material. Drying can increase the usable value of a dried product [1-3]. By reducing the mass of wet material created by evaporation of moisture, drying can improve the strength, longevity of the product, its relief, additional, processing, appearance, shape, color, taste, and many features relevant to the use of the product [4-6].

The most widespread division of drying is natural drying and artificial drying. Natural drying means to leave it in an open space, being exposed to the wind or radiation of the sun, or being exposed to a drying agent - the surrounding gaseous environment. Artificial drying processes are procedures performed by externally organized coercion on moist material in order to accelerate the removal of moisture from the material [3, 7, 8].

2. Material and method

2.1 Description of the process for the production of sodium bicarbonate

Sodium bicarbonate (baking soda) is a white crystalline powder with crystals of 5-200 μm in size and a bulk density of 900 kg / kg. The solubility of sodium bicarbonate in water is low and does not change significantly with temperature.

Due to the low solubility of NaHCO_3 , the suspension is subjected to a suspension of NaHCO_3 in mother liquor. Thus, a solution of alkaline soda of 105-110 ND is obtained. The DCB solution, which is obtained by the "wet" method in the production of calcined soda, concentration 105-110, ND - is pumped into the reservoir of DCB solution and then free flowing into the reservoir of normal solution. In the reservoir of the normal solution, in a certain ratio established by the material balance, the mother liquor and the DCB solution are mixed, and the normal solution thus obtained is transported to the top of the carbonation column by a feed pump. A portion of the normal solution is circulated in the column by a circulation pump.

Gas from lime kilns with a CO_2 content of 38-42% is added to the lower part of the carbonation column at a pressure of 1.5 - 2 bar. Before moving into a column, the gas is cleared of mechanical impurities in the gas purifier [9, 10]. To ensure a sufficiently high absorption rate, the CO_2 content of the gas of the lime kilns must not be less than 38%. At the exit of the carbonization column, the CO_2 content of the gas is reduced to 18-22%. Such gas is discharged into the atmosphere.

The suspension of NaHCO_3 , formed in the carbonization column, is transferred to the decanter by a circulating pump, where it is quenched from the solid: liquid = 1: 1 ratio. The thickened part of the suspension goes to a centrifuge, from which a wet product is inserted into a pneumatic dryer. The overflow from the decanter and the mother liquor behind the centrifuge are transferred to the tank, from which one part is returned to the pipeline of normal solution and the other is sent to the soda plant for suspension of NaCHO_3 crystals.

The pre-centrifugal humidity of the precipitate is at least 8%. Drying takes place in a pneumatic dryer using heated air in the heater to a temperature of 150 ° C. At the outlet of the dryer, the air temperature drops to 55-60 ° C.

Due to the separation of sodium bicarbonate particles, the air passes through the cyclone, behind which is the dust collector. Dry sodium bicarbonate of 45-50 ° C is brought into the hopper, where one part is taken for refining and medical bicarbonate is obtained, and the other part - as technical bicarbonate - is packaged and marketed. A sodium bicarbonate drying plant consisting of a suction fan, a heater, a dozer, a pneumatic dryer, a cyclone and a blower fan is given in Fig. 1.

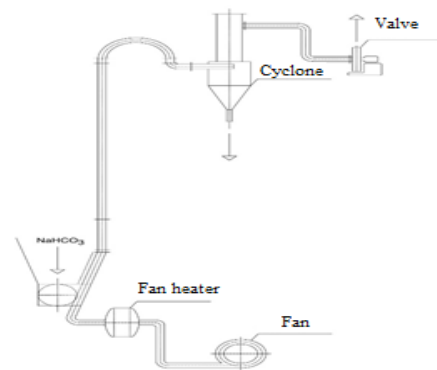


Fig. 1 Sodium bicarbonate drying plant

2.2 Material-energy balance and calculation of the drying process

Table 1: Basic information

Capacity relative to dry product, Gt	1.712 kg/h (15.000 t/year)
Product Humidity: - initial, C_o - final, C_k	(8%) 0,087 kg/kg (0,1%) 0,001 kg/kg
Mean equivalents particle diameter, d_e	35 μm
Particle shape factor, f	1,25
The maximum diameter of the particulate aggregate, d_{max}	200 μm
Product density, ρ_m	2.250 kg/ m^3
Material tempo at input, t_{mo}	20°C
Humidity at the inlet (this = 10 ° C, $\phi_{\text{sr}} = 77\%$)	0,006 kg/kg
The air temperature behind the heater, t_1	140°C
Air temperature at the outlet of the dryer	60°C
Atmospheric mean pressure, p	98.042 Pa

3. Results of research and discussion

3.1 Final humidity calculation

Total moisture losses Δq

$$\Delta q = q_w - (q_b + q_0)$$

$$\Delta q = -859,2 \text{ kJ / kg moisture}$$

Physical moisture heat q_w

$$q_w = c_w \cdot t_{mo}$$

$$q_w = 83,74 \text{ KJ / kg moisture}$$

Warm heat of wet bicarbonate q_b

$$q_b = \frac{Gt + c_0}{W} * (t - t_{mo})$$

$$q_b = 642,9 \text{ kJ / kg moisture}$$

Losses in the environment range from about 120-600 kJ / kg of moisture, and in this case it is adopted

$$q_0 = 300 \text{ kJ / kg of moisture}$$

The amount of moisture that needs to be evaporated within an hour

W

$$W = G_t * (C_0 - C_k)$$

$$W = 147 \text{ kg / h.}$$

Losses reduced to 1 kg of air q'

$$q' = \Delta q * X = \Delta q * (X_2 - X_3)$$

$$q' = 28.9 \text{ kJ / kg air (6.9 kcal / kg air)}$$

Here, X_3 is the final humidity at ideal drying (Diagram in Fig. 2., $X_3 = 0.0397$, $X_2 = 0.006$).

If the calculated values are plotted in the diagram in Fig. 2, the final humidity is obtained:

$$X_k = 0.0324 \text{ kg / kg}$$

$$\varphi = 30\%$$

$$m_p = 56^\circ \text{C}$$

The change in air condition in the bicarbonate drying process is presented in Fig. 2.

Average air temperature in the dryer:

$$t = (140 + 56) / 2 = 98^\circ \text{C}$$

The mean absolute humidity, density, kinematic viscosity, coefficient of conductivity, and temperature coefficient of conductivity have the following calculated values:

Mean absolute humidity

$$\bar{X} = \frac{0.006 + 0.0324}{2} = 0,0192 \text{ kg/kg}$$

Density

$$\bar{\rho} = \frac{p}{2RT} = \frac{98042}{\frac{8314}{28,49} \cdot 371} = 0,92 \text{ kg/m}^3$$

Kinematic viscosity

$$\bar{\nu} = 2,82 * 10^{-5} \text{ m}^2 / \text{s}$$

Conductivity coefficient

$$\bar{\lambda} = 3,09 * 10^{-2} \text{ W / (mK)}$$

Temperature coefficient of conductivity

$$\bar{\alpha} = 3.83 * 10^{-5} \text{ m}^2 / \text{s}$$

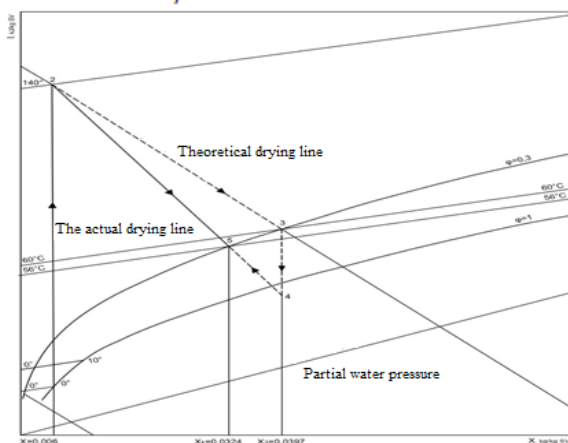


Fig. 2 Drying process On HCO_3 in I-X diagram

3.2 Amount of air to dry

$$L = \frac{W}{X} = \frac{147}{0,0324 - 0,006} = 5034 \frac{\text{kg}}{\text{kg}} \text{ dry air} \quad (9)$$

$$V = \frac{L * (1 + \bar{X})}{\bar{\rho}} = \frac{5034 (1 + 0,0192)}{0,92} = 5585 \text{ m}^3 / \text{h} \quad (10)$$

4. Conclusion

The paper presents one of the many ways of drying baking soda in a dryer with pneumatic material transport.

The calculation of certain parameters that change during the drying process, such as temperature of hitting of wet bicarbonate, physical heat of moisture, amount of moisture to be evaporated, environmental losses, total heat losses, heat losses reduced to 1 kg of air, as well as air volume which is required for drying baking soda [1, 3].

In order to complete the drying process from the aspect of drying agents and wet material involved in the drying process, and based on the given and calculated parameters, an appropriate diagram was defined in which the change of air condition in the bicarbonate drying process was presented [3, 4].

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Innovative design for repair of corrected industrial reinforced concrete structures of light soda silos - Solvay Sodi AD, Devnya

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Abstract: The report discusses the main parameters of a developed design and technological project for the implementation of specific repair and restoration works of built in the mid-1970's corroded concrete reinforced structures of LIGHT-SODA SILOS – SOLVAY SODI JSC. The purpose of the design is to comply with the requirements for reasonable sufficiency of the additional new steel-reinforced concrete coating (jacked) to realize a lightweight variant of the protective layer against corrosive production factors, atmospheric influences and other specific chemical impacts. The project envisages a technological variant for the implementation of an additional healing thin repair reinforced concrete layer (overlay), based on the specific characteristics of high-tech hybrid fiber-reinforced "wet" sprayed concrete with the participation of specially selected high-range water-reducing and internal-crystallization chemical admixtures. The report provides information on the basic physical-mechanical and technological characteristics of the "wet"-sprayed concrete, as well as the main stages of structural design with specific structural details. According to the static scheme of the facility, it is proposed to specify the allowable load-state of the structure during the repair works.

Keywords: CORRODED CONSTRUCTIONS, CONSTRUCTION AND TECHNOLOGICAL DESIGN FOR REPAIR WORKS, HIGH-TECH HYBRID FIBER-REINFORCED "WET"-SPRAYED CONCRETE, HIGH-RANGE WATER-REDUCING AND INTERNAL-CRYSTALLIZATION CHEMICAL ADMIXTURES

1. Introduction

The steel reinforced concrete structures of LIGHT SODA SILOS "4" & "5" - SOLVAY SODI AD, DEVNYA, were built in 1973 and they still operate under the combined impact of exploitation and environmental factors, some of which display significant corrosive potential. The latter violated the quality of the steel reinforced concrete, and serious corrosive damages were located within specific areas - **Photos 1 and 2**.



Photo 1 LIGHT SODA SILOS "4" & "5" general view



Photo 2 LIGHT SODA SILOS "4" & "5" typical concrete damages

The preliminary analysis of possible technical solutions produces a limited number of reasonable options basically due to the specific character of the operational units. Moreover, their operation cannot be entirely excluded from plant's overall operational regime during a reasonable period of time. One should also note the absolute unsoundness of the "by the job" approach to repair, i.e. repair of local areas where the damaged state of the structure has been visually established. This is so since such an approach would indefinitely prolong repair whereas the escalation of corrosion damage would proceed in neighboring areas.

The design and execution of necessary repair/recovery operations based on subsequent technological regulations, concerning the employment of a standard repair systems pursuant to a series of standards **BDS EN 1504: 1-10 Products and systems for the protection and repair of concrete structures**, is also rejected a priori. Otherwise, this would yield the use of standard compatible mixes with different function, deposition of layers with comparatively large thickness and inevitable rise of repair cost.

The conventional construction of an entirely new steel reinforced concrete casing (a monolithic method) yielding increase

of the wall cross section by at least 10 cm, is also unacceptable. Otherwise, the surface of the outer walls would be simultaneously and entirely uncovered resulting in total exclusion of the reinforcement from operation and hazards to the structure safety. Besides, such an approach imposes inadmissible complex requirements to the repair/recovery concrete and rise of cost.

Shotcreting of a new special concrete layer ("jacket"), without the use of formworks, employed to recover the initial cross section, seems to be the most appropriate technological method. Such an approach is adopted as a basic one in the present technical project, where as a technical-economical comparison between the two methods of shotcreting - "dry" and "wet" concrete covering, shows imperative advantages of the "wet" one [1,2]. The design envisages a technological variant for the implementation of high-tech hybrid fiber-reinforced "wet" sprayed concrete with the participation of specially selected high-range water-reducing and internal-crystallization chemical admixtures.

The purpose of the design is to observe the reasonable sufficiency requirements of the new concrete cover above the existing steel reinforcement, and to execute a thin protective overlay with special technical characteristics against the industrial factors influencing corrosion, weather impact, freezing, carbonization, UV rays, etc.

A basic requirement to the project is the observation of the principles of reasonable sufficiency of the offered solutions, concerning optimization of the thickness of the new concrete cover of the reinforcement, deposition of a low-weight anti-corrosion layer, protecting from atmospheric impacts, freezing, carbonation, UV rays etc. In addition, development of technical regulations of the planned repair is also envisaged.

2. Loads and actions on the silos

Considering the nature of the designed repair and renovation works, the structural stability and capacity has been checked in construction stage, taking into account the state of the silo during the repair works. In such a design situation, the silo is partially filled with light soda ash and parts of the body, ring beam or columns are partially weakened. For this purpose, the applied loads have been defined in compliance with **BDS EN 1991-1-6: General actions during execution**. Considering the estimated duration of the repair works per one spraying stage (each one over 3 days) and according to **Table 3.1 of BDS EN 1991-1-6**, the atmospheric loads on the structure were defined with probability of occurrence once in 5 years.

The wind load is determined for terrain **category IV** and base speed with probability of exceeds once in 5 years - 26,5 m/s. The dead loads are defined on the basis of the material volume density and the geometry dimensions of the silo's elements. The load from the gallery above the silo is also reported.

Since a possibility is sought to avoid emptying the silo during the repair works, the calculation analysis has been performed for different degree of filling the silo with soda and respectively at different stages of repair works it can be filled differently. This filling capacity of the silo has been studied via data from the actual material circulation over the years. The records have been submitted by the Assignor and based on them the designer has made his estimation.

The Solvay's engineering team has specified the characteristics of the soda stored in the silo with the following parameters: volume weight: 0,50 t/m³; angle of internal friction 40-45°. This volume weight is confirmed by the fact that at the maximum volume of the silo of ~8300 m³, the maximum filling capacity of silo "4" is 4130 t of soda.

3. Structural survey and status of the elements

The dimensions and location of the structural elements and reinforcement have been defined on the basis of the archive drawings.

Visit and visual inspection of the reinforced concrete structure has been performed to confirm or clarify the records data. The existing reinforcement steel was specified (A-III) as well as the concrete class (grade 300 ~, concrete compressive cube strength is 22,5 MPa). It should be noted that no essential damages have been observed in the reinforcement of the elements. Significant part of it is visible in the areas exposed to weather (the side of the columns, which is in contact with the outside air, the external cylindrical part of the silo body) but the visible reinforcement steel is in relatively good condition. The silo funnel (conical hopper), the supporting ring beam and the internal columns are predominantly in relatively good status and there is almost no visible reinforcement. Damage on the covering of the internal elements is observed only in the areas of leaks between the steel roof structure at level 15,00 and the silo.

4. Bearing capacity of the reinforced concrete structure elements during the repair activities and degree of silo's filling

A calculation check of the silo structure elements has been carried out, which indicates reducing of the element's sizes during the repair activities. For this purpose, the bearing capacity of the separate structural parts and sections of the silos was checked, based on their reduced sections at permissible level (as prescribed by design) of filling the silo for the respective pouring stage.

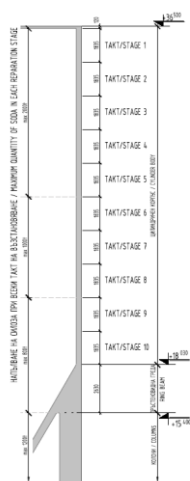


Fig. 1 Maximum permissible soda content during the repair and renovation works

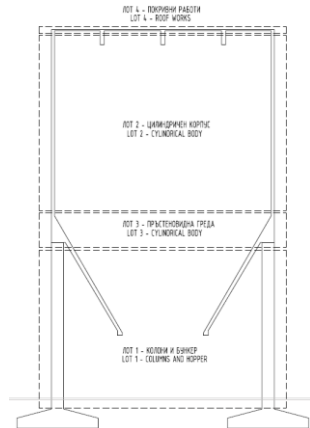


Fig. 2 Sequence of the repairing works

4.1. Different sections of the cylindrical body of the silo

The possibility to reduce the shell structure section after the sandblasting of its surface has been considered, which will cause partial exposure of the external reinforcement. The following has been found:

- In the area of close to the transition between the cone and the cylinder, the section is overexposed to bending moments (also known as edge bending moment area). Critical is the bending capacity in this area, whereas during the repair works the bending capacity checks are fulfilled if the silo contains up to 800 t of soda. The last impose that the silo cannot be filled with more than 800 t of soda at the time pouring stage 9-th and 10-th are ongoing as per **Figure 1**.

- In the area outside the edge bending moment areas, the bending moments have extremely reduced values. Critical shall be the tensile strength of the ring, where part of the reinforcement is exposed and separated from the concrete due to sandblasting. At different operational areas of the silo the degree of possible filling is different and is shown on **Figure 1**.

4.2. Ring beam

The main internal forces within the ring beam are the axial forces and bending moments. Having considered the possibility to reduce the bearing capacity of the element following its sandblasting or hammering, the permissible content of soda is found to be 800 t. This parameter shall be controlled during the repair works on the beam.

4.3. Columns

The silo columns are under bending and compression. A calculation check of the capacity of the columns was done. The damages on the columns are mostly on their external side which is exposed to weather. In this area sandblasting is planned to be performed, installation of reinforcement mesh and applying the wet mix shotcrete process for spraying of concrete coarse aggregate containing **Mix №1** [1]. Prior to the eventual removal of carbonated concrete, it is foreseen that the vertical rods will be braced by stirrups against buckling in view of the compression stresses existent in them. Work on "external" columns can be done with the presence of soda up to 1200 t.

The internal columns, subject to their good status, will undergo only sandblasting of their surfaces and wet mix shotcrete process for spraying of a special passivating restorative without concrete coarse aggregate containing **Mix №2** [1]. They may be processed simultaneously. The degree of permissible filling of the silo during works on all elements is shown on **Figure 1**.

5. Description of the renovation and strengthening measures

Further to the survey and structural analysis made, the following strategy for strengthening and renovation has been adopted. In view of the necessity to reduce the quantity of soda contained in the silo during the repairs, the works on each of the silos shall be done separately. Having analyzed the data provided by the Client about the degree of filling the soda ash light silo per month for the year 2017 till issuing the design, it was found that if the silo operate separately, the total quantity of soda produced could be stored at the reduced capacity of the silo undergoing repairs as per the requirements of the present design.

The sequence of renovation follows like this – **Figure 2**:

- Lot 1 – columns and hopper;
- Lot 2 – cylindrical body;
- Lot 3 – ring beam.

5.1. Columns

The columns are classified as two types - **Type 1** and **Type 2** according to **Figure 3**. The **Type 2** columns are not in direct contact to the outside environment and visually look in very good condition. Damages are observed on the columns which are in

contact with the outside weather conditions (**Type 1**). These areas include the possibility of carbonated concrete being removed, the reinforcement of the longitudinal and transverse reinforcement, and installation of a technological reinforcement mesh and the spraying of the **Mix №1**.

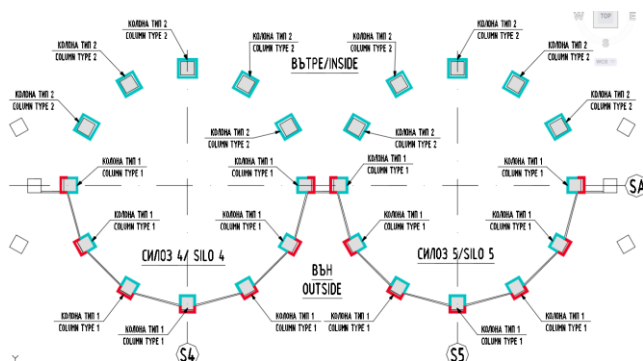


Fig. 3 Columns classifications

For the internal columns (**Type 2**), only wet mix shotcrete spraying of special repair, restorative and passivating **Mix №2** as per specifically developed recipe is planned.

The repairing works on each column are to be executed independently for the upper and the lower half.

Sequence of working on the one half (upper or lower) of the column:

- the soda content shall be compliant to the values on **Figure 1** (1200 t);
- The concrete cover in the repaired zone is removed in order the top surface of the existing bars to be visible (**Figure 4**). **If healthy non-carbonated concrete is reached before uncovering the bar's surface, no more concrete to be removed;**
- Execution of vertical bars fixing by bonding bars C1 and bars are fixed by welding (**Figure 5**);
- Checking the stage of carbonization in areas with removed concrete cover;
- The areas with stated carbonization are to be marked and the concrete around each bar is to be removed until healthy concrete is reached, but not to be reached deeper than 80 mm from the original dimensions of the section (**Figure 6**). **If in some zone healthy concrete is reached, before uncovering some reinforcement bar, that concrete should not be removed and the bar remains uncovered;**
- The existing reinforcement is being repaired by welding if necessary;
- Welded meshes are applied by anchoring hooks;
- Shotcreting by **Mix №1**, and forming the surface by side formwork;
- After removing of the side formwork transition should be sprayed with **Mix №2** (**Figure 7**).

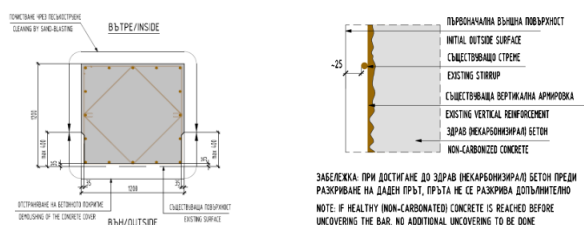


Fig. 4 First stage of the preparation – concrete cover removal for columns Type 1

5.2. For the cylindrical part of the silo above level +18,03

For this part of the silo repair works from top to down are planned in spraying stages with height ~1,8 m along the perimeter of the cylindrical part. After making the soda content compatible to the values shown on **Figure 1**, the processed area shall be sandblasted in order bars' surface to be uncovered (**Figure 8**) while

not penetrating further below the reinforcement unless happens during the blasting due to local damages in the reinforced concrete section. The carbonation degree is being checked and the carbonated areas should be marked. The carbonated concrete around each bar is to be removed but it should not be reached more than 20 mm behind the vertical reinforcement. If noncarbonated concrete is reached before uncovering the bars, no additional uncovering to be done (**Figure 9**).

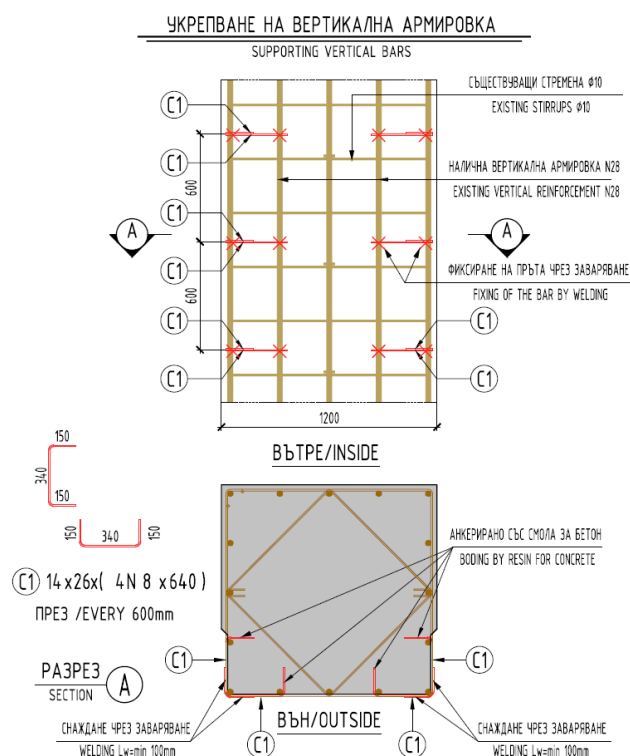


Fig. 5 Existing bars fixing

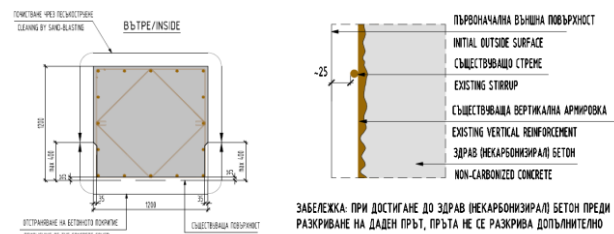


Fig. 6 Second stage of preparing – removal of carbonated concrete

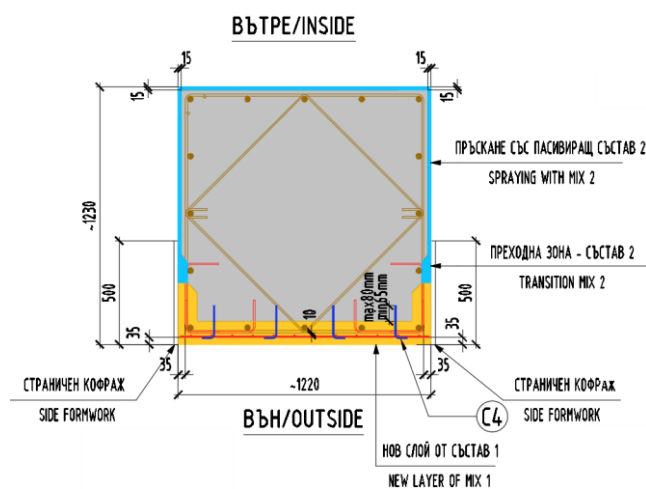


Fig. 7 Repaired section

Upon finding of interrupted reinforcement bars or damaged overlapping joints, then they shall be joined by welding details.

Over the cleaned surfaces, welded reinforcement meshes N6/ (150x150 mm) are installed. They are installed via anchoring of the reinforcement bars in the concrete at a distance of up to 300 mm at both sides (anchoring depth 80 mm - **Figure 10**). Point fixators (rebar spacers) shall be additionally installed, too. They serve as reference points when forming the cylinder curve after applying the shotcrete.

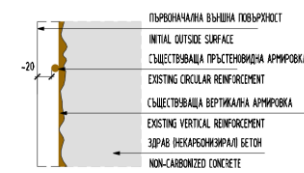


Fig. 8 First phase of carbonated concrete removing in the cylindrical body

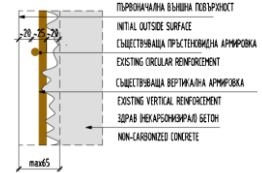


Fig. 9 Second phase of carbonated concrete removing in the cylindrical body

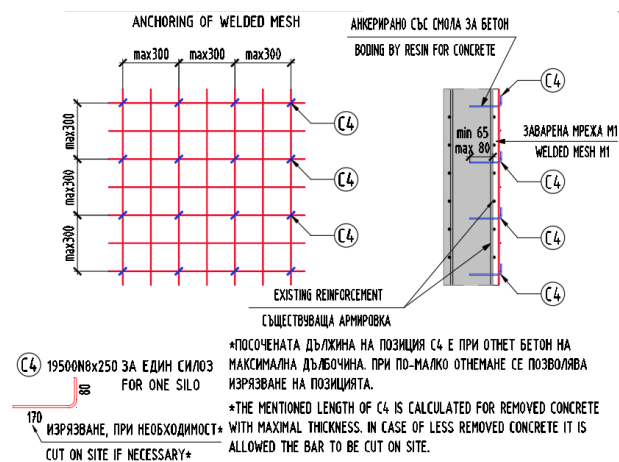


Fig. 10 Anchoring rods for reinforcing mesh

Once the blasting and reinforcement works are finished, follows the wet mix shotcrete process of spraying **Mix №1** as per specifically developed recipe. Two days afterwards the next spraying stage shall be prepared. There is an exception only when moving from spraying stage 10 to the ring beam. Then this period is four days afterwards.

5.3. For the ring (support beam)

The impairments of the ring beam include damages on its concrete cover in the areas exposed to weather and leaks. Installation of reinforcement is planned to be executed and shotcreting of **Mix №1**.

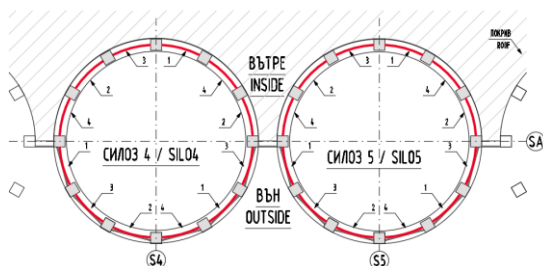


Fig. 11 Scheme of sequence of the reparation works

*No more than three bays are allowed to be treated at the same time/ the ones with same number acc. figure 20, and next group of bays can be started at least four days after finishing the previous ones/.

- The permissible soda content in the silo during the repair works on the ring beam is shown on **Figure 1** – 800 t;
- The concrete cover of the bay is removed in order the top surface of the existing bars to be uncovered;
- The degree of carbonation is checked;
- If reached concrete is not carbonated, welded meshes to be installed by anchoring bars C5. **Mix №1** to be applied;
- If there are areas with carbonized concrete, they must be marked. The next repairing works must be executed in zones including maximum the number of bars quoted. If healthy concrete is reached before uncovering an entire cross-section of the bar in the working zone, no more concrete to be removed. Every next zone to be started after the reinforcement installing, shotcreting and strengthening the previous zone are finished (**Figures 12-14**).

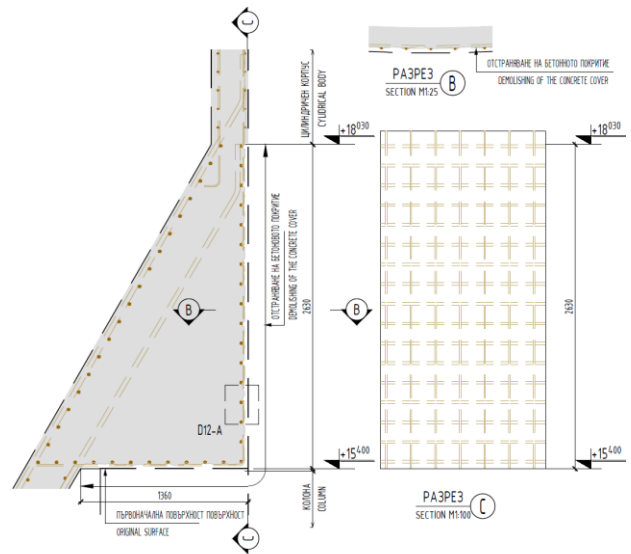


Fig. 12 Uncovering top surface of the existing bars in the treated bay

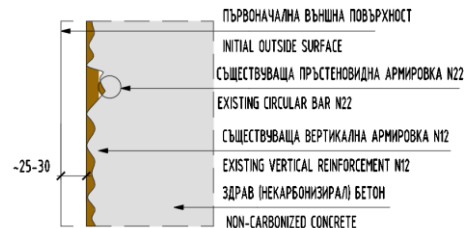


Fig. 12 Uncovering top surface of the existing bars in the treated bay

In the areas of the additionally built roof structure, works on the ring beam shall be carried out without dismantling the roof structure. The areas above the roof shall be treated first and the roof sheet can be cut so that the reinforcement mesh can pass underneath. When the area above the roof is finished, the one below the roof is processed. Steel structures or concrete elements shall not be dismantled. No more than 25 mm (measured from the original sizes of the section) concrete to be removed in the area of the embedded items.

5.4. Cone funnel (hopper)

In view of the good status of the conical part of the silo (the hopper), surface processing is planned including the following activities:

- sandblasting;

- dust-removal treatment;
- polymeric composition primer;
- thin passivating polymer covering applied by roller.

Acknowledgments

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7. References

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2. V. Naidenov, M. Mironova, Innovative hybrid fiber-reinforced shotcrete for thin repairing concrete overlays, VI-th International Congress INNOVATIONS'2020, 22-25.06.2020, Varna, 2020, (to be published)

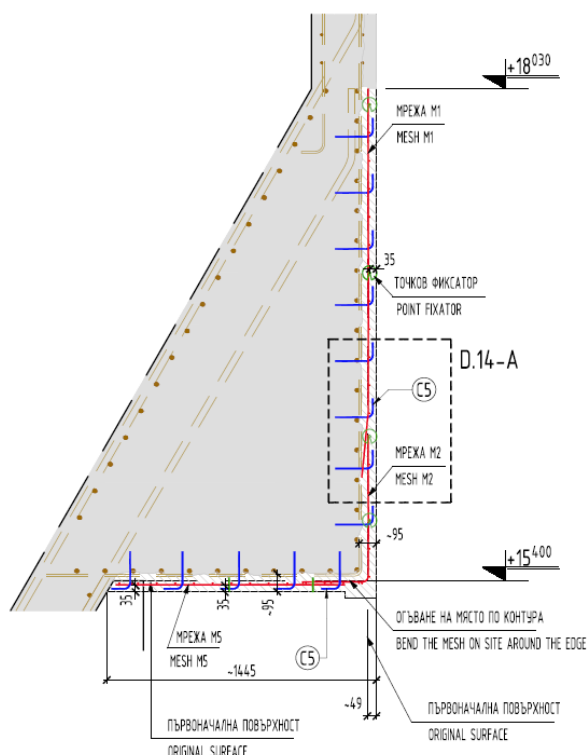


Fig. 13 Repairing works of the bays if non-carbonized concrete is reached in uncovering the top surface of the bars

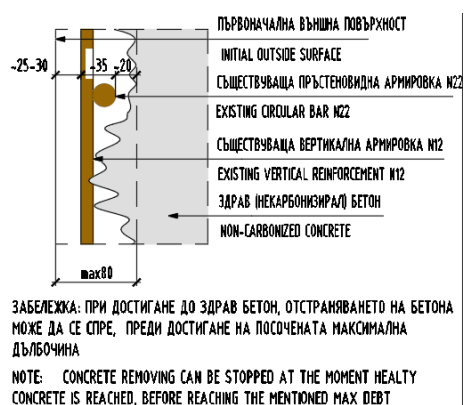


Fig. 14 Additional uncovering the bars if concrete is carbonated

6. Conclusions

The specific innovative design of repairing works needed is presented. Based on wet-shotcreting works the proposal contains all necessities stages – static calculations, specific detailing, technological approaches and working stages.

Using new developed wet shotcrete mixes with hybrid reinforcement (steel mesh and micro-polypropylene fibres) and new range of internal crystallization admixture gives attractive prospects for optimal repairing works to be executed. Nowadays the design developed is in progress.

Regularities of influence of electron beam technology on heat resistance of optical elements in precision instrument-making

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Abstract: Existing experimental researches show that in order to prevent the destruction of optical elements of modern opto-electronic devices (discs as the light filter linings for IR devices, the input protective windows of laser sighting systems for observation in IR areas of the spectrum, semispherical fairings of IR devices for homing and observation of objects, lightguides for laser medical devices, etc.), electron beam method becomes promising, as it provides cleaning of surfaces, increases their microhardness, makes them more resistant to external influences. The results of experimental studies to improve the properties of the surface layers of elements from optical ceramics after their processing with a moving electron beam with a heat density $F_n = 10^6 \dots 1.6 \cdot 10^7$ W/m² and moving speed $V = 10^{-3} \dots 10^{-1}$ m/s (increase in the surface microhardness from 1.2 ... 2.9 GPa (raw elements) to 5.7 ... 6.4 GPa (processed elements), the occurrence of hardened layers with a thickness of 210... 230 microns). It has been established that the improvement of these properties leads to an increase in the resistance of elements to external thermal effects: an increase of 1.3...1.7 times the critical values of external heat flows and their exposure times, exceeding which leads to the destruction of elements and the failure of devices for the studied range of change of external pressure is $10^5 \dots 10^7$ Pa; increasing the maximum allowable values of thermoelastic stresses in elements from 50...140 MPa to 160...370 MPa at heating temperatures of 300...1200 K.

Keywords: Precise instrument making, Optical ceramics, Electron beam, Microstructure, Hardness, Thermoelastic stresses.

1. INTRODUCTION

Modern opto-electronic devices with elements from optical ceramics (KO1, KO2, KO3, KO5, KO12, etc.) (discs as the light filter linings for IR devices, the input protective windows of laser sighting systems for observation in IR areas of the spectrum, semispherical fairings of IR devices for homing and observation of objects, lightguides for laser medical devices, etc. [1 – 4]), under the conditions of their operation, can be subjected to intense external thermoactions (elevated heating temperatures and external pressures, shock thermal actions under shot and flight conditions, etc.).

Under these conditions there is a significant change in the properties of surface layers of optical elements up to their destruction (the emergence of cracks, chips, and other defects), which leads to a significant deterioration in the technical and operational characteristics of the devices (reliability, service life, etc.) and their failure.

Therefore, prevention of these non-desirable phenomena is relevant at the stage of design and manufacturing of devices with the concerned fairings.

Existing experimental researches [5 – 9] show that in order to prevent the destruction of optical elements, electron beam method becomes promising, as it provides cleaning of surfaces, increases their microhardness, makes them more resistant to external influences.

Now the researches on prevention of possible destruction of optical elements of precise instrument making under the conditions of their operation, taking into account the influence of external thermoactions, are absent. In addition, the issue of influence of the thermal action of an electronic beam on the surface of optical elements for their resistance to external thermoactions is not studied enough: optimal change ranges of electronic beam parameters (density of thermal effect, movement velocity), within which there is a significant improvement of the properties of surface layer of elements, increasing their resistance to heat loads and, ultimately, the improvement of the technical and operational characteristics of the devices.

Thus, the purpose of the work is to prevent the destruction of elements from optical ceramics of optical-electronic devices by improving the properties of surface layers of elements and increasing their resistance to external thermoactions by means of finishing electron-beam processing.

2. METHODOLOGY AND SETTINGS FOR CONDUCTING THE RESEARCHES

In order to study the influence of electronic beam parameters on the properties of surface layers of elements from optical ceramics (KO1, KO2, KO3, KO5, KO12) the discs were used with diameter of $3 \cdot 10^{-2} \dots 5 \cdot 10^{-2}$ m and thickness of $4 \cdot 10^{-3} \dots 6 \cdot 10^{-3}$ m, semi-spherical fairings with diameter of $4 \cdot 10^{-2} \dots 8 \cdot 10^{-2}$ m [1, 5]. For researching thermal actions of the movable electronic beam on the element from optical ceramics the following equipment was used developed by the authors. This is specialized specialized electron-beam equipment, which is protected by the patent of Ukraine, which allows to implement tape electronic beam with the width of $5 \cdot 10^{-4} \dots 5 \cdot 10^{-3}$ m, length of $6 \cdot 10^{-2} \dots 8 \cdot 10^{-2}$ m, density of thermal action $F_n = 5 \cdot 10^6 \dots 9 \cdot 10^8$ W/m² and movement speed $V = 5 \cdot 10^{-3} \dots 10^{-1}$ m/s.

Electron beam equipment and its basic elements The equipment is created on the basis of universal vacuum installation УВН-74ПЗ [1]. Vacuum system consists of a vacuum chamber and a vacuum installation post УВН-74ПЗ, steam-oil diffusion pump НП-400, forvacuum pump АВЗ-20, vacuumeters ВИТ-3, and ВМБ-8, vacuum sensors (Thermocouple ТП-1, ionic ИП-1, magnetic-blocking М-2) located in the vacuum volume. In the vacuum chamber of the installation there is a special technological equipment for electronic processing, namely: quartz infrared furnace of previous heating and final cooling, electronic gun with Pierce optics for forming of tape electron flow, mechanism of optical elements moving. Provide the work of special technological equipment the following external devices, namely: high-voltage power supply of electronic gun based on the unit УЭЛИ-1, quartz furnace control unit based on the thermal sensor-thermostat РИФ-101, he automated processing control system is developed.

To simulate thermal influences on the investigated elements under normal conditions ($T_0 = 293$ K, $P = 10^5$ Pa) and find the critical values of their parameters (heat flow q_{cr} and the time of its effect t^*), exceeding of which led to the destruction of optical elements, they used guided IR heating by quartz lightbulbs КТТ-220-1000-1, by using the thermal sensors РИФ-101 to control the surface temperature of the elements in the range 300... 1900 K and heat flows that come to them.

To simulate the effects of elevated heating temperatures (up to 1500 K) and external pressures (up to 10^7 Pa) the standard installation was used, where the tests were carried out by methods worked out at "Zavod Arsenal" (Plant Arsenal) (Kyiv) and at

Cherkassy State Technological University within the framework of joint state budget and state contractual research works [1].

To determine the properties of optical elements before and after electron beam processing (microhardness of the surface (H_v , MPa), the magnitudes of residual thermal stresses (σ , MPa) and thickness of strengthened layers (Δ , microns) they used the known methods of physicochemical analysis (microindentation by Vickers method, optical microscopy and microdiffraction analysis, which include raster and scanning microscopy (REM) and transmission electron microscopy (TEM), general-duty diffractometers ДРОН-0,5, ДРОН-2,0, ДРОН-3,0 with special consoles for measuring the microvoltages in surface layers, etc. [1]. The hardness boundary of the optical elements $\sigma^*(T)$ before and after electron-beam processing were found by the central-ring bend (CRB) [5].

The relative error was not higher than 5... 10% in the conducted studies, aimed to determine the above-mentioned properties of the surface layer of optical elements and critical values of the external influences parameters.

3. RESEARCH RESULTS AND THEIR ANALYSIS

It has been established that for the parameters of an electronic beam change ($F_n = 10^6 \dots 1.6 \cdot 10^7 \text{ W/m}^2$, $V = 10^{-3} \dots 10^{-1} \text{ m/s}$) surface element microhardness varies from 1.2...2.9 GPa (for raw items) to 5.7...6.4 GPa (for the processed items). In this case, an increase of F_n of 10^6 W/m^2 до $1.6 \cdot 10^7 \text{ W/m}^2$ leads to an increase of the microhardness of the ceramic surface by 1.5...1.7 times, and an increase of V from 10^{-3} to 10^{-1} m/s leads to a reduction of microhardness of the ceramic surface by 1.3...1.4 times (Fig. 1).

The results of the research on changes of microhardness at the depth of elements from optical ceramics, which are processed by electron beam, are presented in Fig. 2. From this data it follows that the material microhardness of all types of considered ceramics is rapidly decreasing, heading to its value for the raw material. The thickness of the strengthened layer (Δ), where there are basic structural changes and the microhardness of the processed material increases for the considered parameters of the electronic beam changes in the range from 70...90 microns to 210... 230 microns at the thicknesses of the processed items of $4 \dots 6 \cdot 10^{-3} \text{ m}$. Value Δ significantly depends on the nature of ceramics, as well as the parameters of electronic beam (fig. 3): F_n increase from 10^6 W/m^2 to $2 \cdot 10^7 \text{ W/m}^2$ leads to an increase in the thickness of the strengthened layer by 1.8...2.6 times, and increase of beam flow velocity from $1.5 \cdot 10^{-3} \text{ m/s}$ to $2 \cdot 10^{-2} \text{ m/s}$ leads to a decrease in the thickness of the strengthened layer by 1.7...2.5 times.

It was established that the influence of an electronic beam on the surface of elements from optical ceramics leads to an increase of mosaic blocks and reduction of micro-deformation of the crystalline lattice: the size of mosaic blocks from the output to processed by electron beam of optical elements increases by 3.9 times for elements of optical ceramics KO1, by 5.5 times for elements of optical ceramics KO2, by 3.3 times for elements of optical ceramics KO12, by 4.7 times for elements of optical ceramics KO3 and by 7.7 times for elements of optical ceramics KO5, and the magnitude of microdeformation decreases by 3.7 times for elements of optical ceramics KO1, by 5.4 times for elements of optical ceramics KO2, by 4.2 times for elements of optical ceramics KO12, by 5.5 times for elements of optical ceramics KO3 and by 5.9 times for elements of optical ceramics KO5.

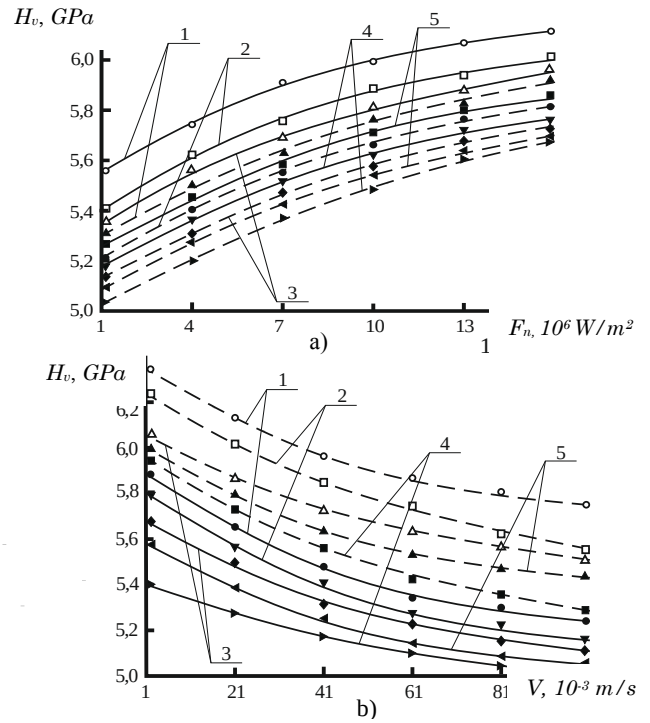


Fig. 1 - Dependencies of element surface microhardness of optical ceramics KO12 (1), KO2 (2), KO1 (3), KO5 (4) and KO3 (5) that are processed by electron beam: a) – from the density of its thermal effect (— — — — $V = 7 \cdot 10^{-3} \text{ m/s}$; — — — — $V = 1.5 \cdot 10^{-2} \text{ m/s}$); b) from the speed of its movement (— — — — $F_n = 2.3 \cdot 10^6 \text{ W/m}^2$; — — — — $F_n = 1.4 \cdot 10^7 \text{ W/m}^2$); Δ , $\circ$, $\square$, $\blacktriangle$, $\blacksquare$, $\blacklozenge$, $\blacktriangledown$, $\bullet$, $\blacktriangleright$, $\blacktriangleleft$ – experimental data.

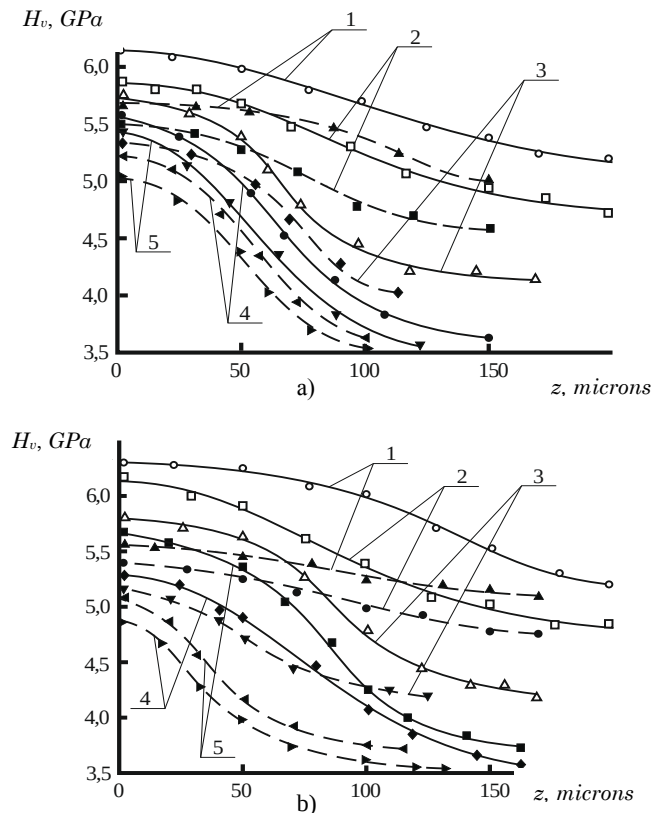


Fig. 2 – Dependencies of microhardness at the depth of elements of optical ceramics KO12 (1), KO2 (2), KO1 (3), KO3 (4) and KO5 (5), processed by electron beam: a) - for different speeds of movement (— — — — $V = 7 \cdot 10^{-3} \text{ m/s}$; — — — — $V = 1.5 \cdot 10^{-2} \text{ m/s}$) and $F_n = 1.5 \cdot 10^7 \text{ W/m}^2$; b) - for different values of its thermal effect density (— — — — $F_n = 1.5 \cdot 10^7 \text{ W/m}^2$; — — — — $F_n = 5 \cdot 10^6 \text{ W/m}^2$)

ma $V = 7 \cdot 10^{-3}$ m/s; Δ , $\circ$, $\square$, $\blacktriangle$, $\blacksquare$, $\blacklozenge$, $\blacktriangledown$, $\bullet$, $\blacktriangleright$, $\blacktriangleleft$ – experimental data.

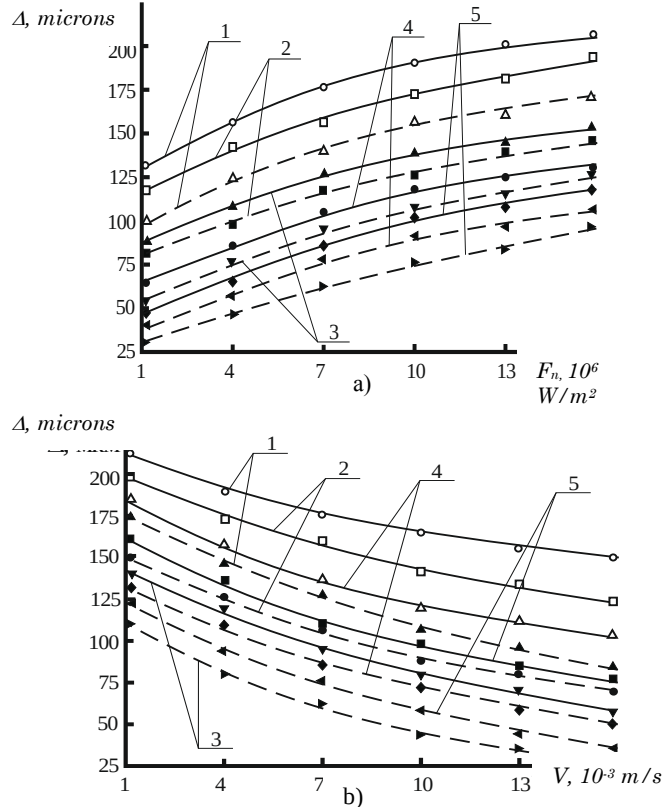


Fig. 3 – Dependencies of thickness in strengthened layers of elements of optical ceramics (1), KO2 (2), KO1 (3), KO3 (4) and KO5 (5), processed by electron beam: a) – from the density of its thermal effect (— $V = 7 \cdot 10^{-3}$ m/s; - - - $V = 1.5 \cdot 10^{-2}$ m/s); b) – from the speed of its movement (— $F_n = 1.6 \cdot 10^7$ Bm/m²; - - - $F_n = 2 \cdot 10^6$ Bm/m²); Δ , $\circ$, $\square$, $\blacktriangle$, $\blacksquare$, $\blacklozenge$, $\blacktriangledown$, $\bullet$, $\blacktriangleright$, $\blacktriangleleft$ – experimental data.

Analysis of the obtained changes of parameters of the crystalline lattices of elements after the electronic processing according with the known methods of data calculation of X-ray patterns [1, 5] based on direct analytical dependence between residual stress, acting on the surface of the element and changing the period of the crystalline lattice of the main components of the considered ceramics, showed the presence of compressive stresses in the thin surface layers of the elements at depth of 40...60 microns for the central part of the processed areas (size of the sections $4 \cdot 10^{-2} \dots 5 \cdot 10^{-2}$ m) in the observed parameter ranges of electronic beam changes: for elements of optical ceramics KO2 by 60...70 MPa; for elements of optical ceramics KO3 by 25... 30 MPa; for elements of optical ceramics KO5 by 55... 65 MPa; for the elements of optical ceramics KO12 by 75... 90 MPa.

As a result of the studies, it was found that after the electron-beam processing of optical elements there is an increase in the critical values of external heat flows q_n^* and the time of their action t^* by 2...4 times (Fig. 4). Thus, the increase in external pressure up to 10^7 Pa, which can be implemented, for example, in the front of the shock wave at a supersonic air flow of the IR device fairings under the conditions of shot and flight, leads to an increase in the values of q_n^* and t^* only by 1.3...1.7 times (Fig. 5).

In addition, it has also been shown that the maximum permissible values of thermoelastic stresses σ^* at different heating temperatures of T for optical elements, processed by an electronic beam, are 1.8...2. 7 times higher than for raw elements (fig. 6).

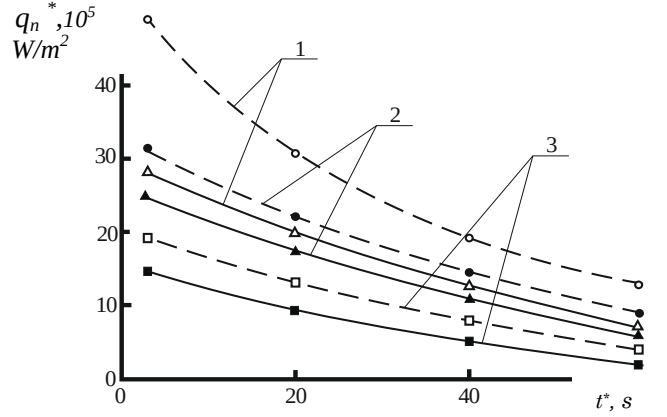


Fig. 4 – Critical value dependencies of external heat flows q_n^* from the time of their action t^* on the optical elements processed and unprocessed by electron beam (element thickness $H = 4 \cdot 10^{-3}$ m, $T_0 = 300$ K, $P = 10^5$ Pa): — — — unprocessed elements; - - - - processed elements ($F_n = 1.6 \cdot 10^7$ W/m², $V = 10^{-3}$ m/s); elements of optical ceramics KO5 (1), KO1 (2) and KO12 (3); Δ , $\circ$, $\square$, $\blacktriangle$, $\blacksquare$, $\bullet$ – experimental data.

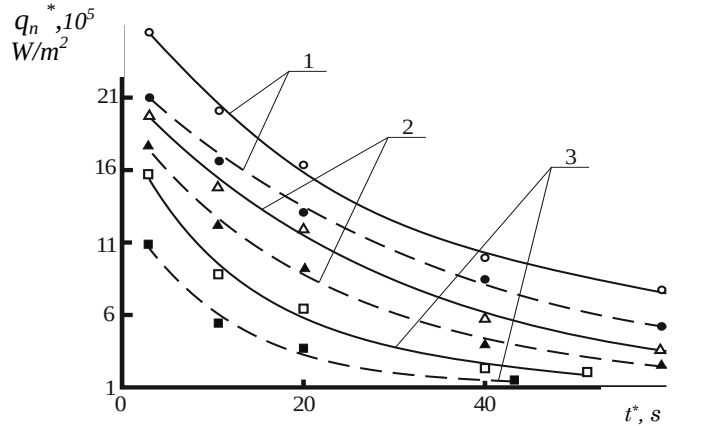


Fig. 5 – Critical value dependencies of external heat flows q_n^* from the time of their action t^* on the optical elements processed and unprocessed by electron beam (element thickness $H = 6 \cdot 10^{-3}$ m, $F_n = 1.6 \cdot 10^7$ W/m², $V = 10^{-3}$ m/s): — — — $P = 10^5$ Pa; - - - - $P = 10^7$ Pa; elements of optical ceramics KO5 (1), KO1 (2) and KO12 (3); Δ , $\circ$, $\square$, $\blacktriangle$, $\blacksquare$, $\bullet$ – experimental data.

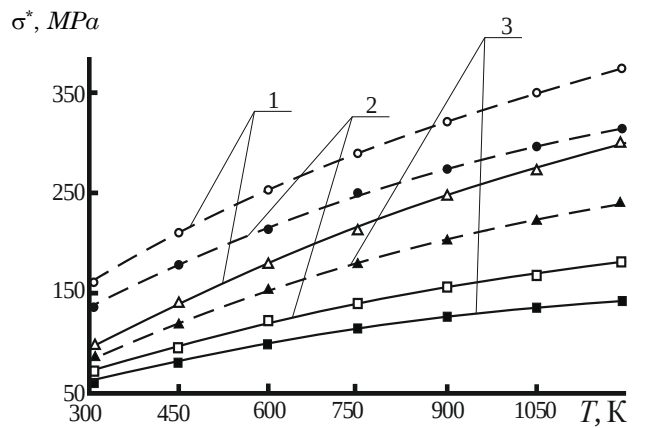


Fig. 6 – Dependencies of values of maximum thermoelastic stresses in the elements of optical ceramics KO1 (1), KO2 (2), KO3 (3) from the heating temperature ($P = 10^5$ Pa, thickness of the element $H = 4 \cdot 10^{-3}$ m, $F_n = 1.6 \cdot 10^7$ W/m², $V = 10^{-3}$ m/s): — — — elements unprocessed by electron beam; - - - - processed elements; Δ , $\circ$, $\square$, $\blacktriangle$, $\blacksquare$, $\bullet$ – experimental data.

4. CONCLUSION

1. It is established that after the processing of working surfaces of elements of optical ceramics (KO1, KO2, KO3, KO5, KO12) by the movable electron beam for optimum ranges of its parameter changes (density of thermal effect $F_n = 10^6 \dots 1.6 \cdot 10^7 \text{ W/m}^2$ and its speed of movement $V = 10^{-3} \dots 10^{-1} \text{ m/s}$) there improved basic properties of their surface layers:

- surface element microhardness varies from 1,2...2,9 hPa (for raw items) to 5,7...6,4 hPa (for the processed items). In this case, an increase of F_n of 10^6 W/m^2 до $1.6 \cdot 10^7 \text{ W/m}^2$ leads to an increase of the microhardness of the ceramic surface by 1,5...1,7 times;
- in surface layers with thickness of 40... 60 microns there appear compressive thermoelastic stresses with the value of 25... 90 MPa, which lead to the formation of strengthened layers up to 210... 230 microns thick;

- it was established that the influence of an electronic beam on the surface of elements from optical ceramics leads to an increase of mosaic blocks and reduction of micro-deformation of the crystalline lattice.

2. It is obtained that the improvement of properties in the surface layers of optical elements after their electron beam processing leads to an increase in the resistance of the elements to external thermoactions:

- the critical values of external heat flows and the time of their action increase by 2... 4 times, which lead to the destruction elements; thus, the increase of the external pressure from 10^5 Pa to 10^7 Pa decreases the specified critical values of parameters by 1.3... 1.7 time;
- the maximum allowable values of thermoelastic stresses increase by 1.8... 2.7 times in optical elements, processed by electronic beam, for the change ranges of heating temperatures 300... 1200 K.

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Influence of technological parameters of FDM-print on the strength characteristics of samples of polyamide

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Abstract: *The article presents the results of a study of the influence of technological parameters of FDM-printing of samples based on aliphatic polyamide on the deformation and strength characteristics of products based on it. The anomalous nature of the increase in the tensile strength during the destruction of samples obtained by increasing the print speed is shown. A decrease in the strength of the samples was noted with an increase in the number of simultaneously printed products. The main factor determining the strength characteristics of FDM products is interlayer autohesion. The need for the use of materials science solutions that contribute to an increase in interlayer interaction in products obtained by layer-by-layer deposition is indicated.*

Keywords: FDM-PRINTING, NYLON, TECHNOLOGICAL PROPERTIES, STRENGTH

1. Introduction

Rapid prototyping technologies are currently used to create working models of simple parts and aggregate mechanisms. Fused deposition technology (FDM), developed in 1992 by Scott Crump, is used in mechanical engineering. FDM prototyping technology uses three-dimensional objects, based on solid-state models created in computer-aided design software (CAD), to create products. Low strength of the finished product in combination with limited accuracy in shape and size is the main disadvantage of this printing technology [1]. The high level of residual thermal stresses that create subsequent deformation and shrink of the product is the main reason for this. The mechanical properties of the resulting product are anisotropic due to the layered and oriented method of guiding the consumable polymer. In addition, the seams between the layers in the product are noticeable, which affects the final roughness of the finished model. Of course, products made by the FDM method are inferior to the method of stereolithography in the accuracy of size and shape, but the FDM method has found wide application due to the low cost of manufacturing the product, as well as the comparative ease of handling a 3D printer in most design tasks [2]. The mathematical model of the product created in the CAD system is written in the stl-format, after which it is transferred to a special slicer program for controlling FDM technology. The program orientates the product, breaks it into horizontal sections (layers) and calculates the paths of movement of the print head. If necessary, supporting structures are automatically generated for overhanging fragments of the product.

ABS-plastics are the most popular 3D printing supplies. This polymer is odorless, non-toxic, melts at 220-240 °C. The material has high dimensional stability. It is traditionally used for the manufacture of automobile parts, stationery, housings, household appliances, furniture, sanitary ware, as well as in the manufacture of toys, souvenirs, sports equipment, and medical equipment using injection molding technologies. Its main drawback is its sensitivity to ultraviolet rays and precipitation. To solve these problems and obtain parts with a high level of performance, filament manufacturers for FDM printers offer polyamide under the general trade name Nylon. For all the advantages of this material, one should also be aware of its shortcomings, which include: high hygroscopicity (up to 12 wt.%), sensitivity to print parameters (print speed and temperature, cooling mode, etc.).

It is known that one of the main factors determining the deformation-strength characteristics of polymer products obtained by the FDM technology of 3-dimensional printing is the nature of the interlayer auto-adhesion of the polymer. Interlayer autohesion is a type of adhesion that characterizes the interlayer interaction of surfaces of polymers homogeneous in chemical composition [3]. Autohesion determines the basic properties of a product, its strength and durability. Issues of autohesion are especially relevant in the manufacture of large-sized products and serial printing due to the significant temperature difference between successively applied polymer layers. Low autohesion combined with high shrink stresses

cause warping, deformation and premature failure of 3D products. This is appeared when the temperature and speed parameters of printing are incorrectly selected most clearly [4]. The problems of autohesion of polymer layers in products obtained by FDM printing are currently poorly understood and consumers of polymer filament for 3D printing rely on the recommendations of manufacturers of equipment and supplies for printing. In [5], the authors found out the effect of 3D printing technological parameters on the interlayer interaction in semi-finished products based on ABS plastic and polylactide (PLA). In [5], the authors found out the effect of 3D printing technological parameters on the interlayer interaction in semi-finished products based on ABS plastic and polylactide (PLA) and established an increase in autohesion interaction with an increase in the contact temperature of polymer layers.

2. Research methods

Establishing the influence of technological parameters of 3D printing of samples based on aliphatic polyamides, most often used as structural materials in the manufacture of engineering products, on the deformation-strength characteristics of the resulting products is the aim of this work. High deformation-strength (σ_s not less than 60 MPa) and tribotechnical characteristics (self-lubricating compositions) in combination with an acceptable cost are among the main advantages of these materials.

Polyamide 6 (PA6) from the manufacturer SANVIGOJ (China) in the state of delivery of the filament with a diameter of 1.75 mm was used as an object of study. Printing standard samples in the form of blades type 1 according to GOST 11262-80 in various settings of the 3D printer was performed for research. The 3D printer FlashForge Dreamer in combination with the «CraftWare 1.19» slicer-program, which provides the necessary print settings, was used to print standard samples. Previously, the polymer filament was subjected to temperature control in an oven at a temperature of 95 ± 5 °C for 4 hours to reduce the moisture content of not more than 0.01 wt.%. The deformation-strength characteristics of the test samples were evaluated on a tensile testing machine RM-500 in the uniaxial tension mode at a speed of 50 mm / min with fixation of the strain and the corresponding tensile force. Printing of polymer blades in the established test modes was carried out in an amount of at least 5 sets for the reliability of the research results. The results were processed using mathematical statistics methods using the Microsoft Excel 2010 spreadsheet editor. Thermophysical processes that occur when a polymer filament based on polyamide 6 is heated were carried out on a Termoscan-2 derivatograph in the differential thermal analysis (DTA) mode when the test sample was heated in quartz crucibles in an air atmosphere at a rate of 5 °C / min.

3. Results and discussions

DTA analysis of the studied polymer material showed a narrower range of the endothermic melting effect of PA6 (Fig. 1) in the range of 240-270 °C in comparison with the recommended printing temperature range of the studied filament in the range of 240-270 °C.

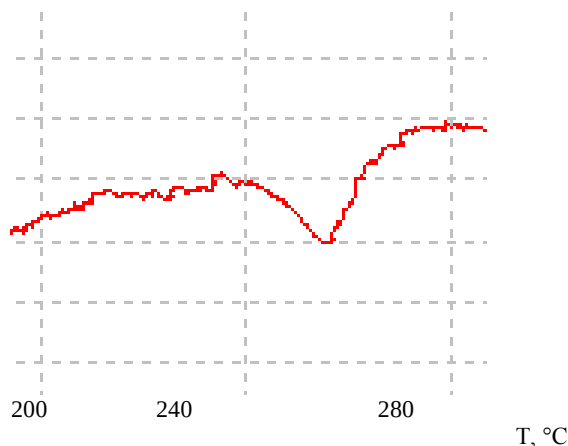


Fig. 1 Fragment of a thermogram DTA filament Nylon SANVIGOJ (PRC)

To achieve satisfactory results of 3D printing of products based on polyamides, it is recommended not to exceed the temperature of the heating of the print table above 70 ± 3 °C. In addition, to avoid warping and peeling in this work, a coating based on polyvinylpyrrolidone (PVP) was used as an adhesive for printed products. In this case, the residual traces of PVP coating on the back side of the printed samples did not significantly affect their strength characteristics due to the high fragility of the adhesive [6]. The influence of the print temperature of the samples was studied at a print speed of 40 mm / s and a print layer height of 200 μ m using a mesh structure to fill the sample volume and its location at an angle of 45 ° to the axis of extension of standard blades. It was shown that an increase in the print temperature of samples within 240–265 °C leads to an increase in the tensile strength (Fig. 2), which is consistent with the conclusions of the authors of [5]. In this case, 260 °C should be considered the optimum printing temperature, since a subsequent increase in temperature leads to an increase in the level of internal stresses, which in turn is due to an increase in the temperature gradient between the applied and the previous polymer layer. This assumption is supported by the fact that the relative elongation during fracture of the samples does not exceed 5%.

It is generally accepted among users of FDM printing technology that the minimum print speed (less than 20 mm/s) combined with the minimum print layer thickness (less than 100 microns) allows to achieve high accuracy in the dimensions and geometry of the product. However, it was shown in [7] that the strength characteristics of various grades of polyamides reach their maximum values when the thickness of the printed layer increases to a value corresponding to the diameter of the nozzle of the printing extruder. In addition, the influence of the extrusion rate on the autohesion processes of interlayer interaction in the process of FDM printing should be taken into account. Thus, a study of the effect of print speed on the strength characteristics of standard samples based on PA6 (Fig. 3) indicates the need for additional studies to explain the nature of the established dependence.

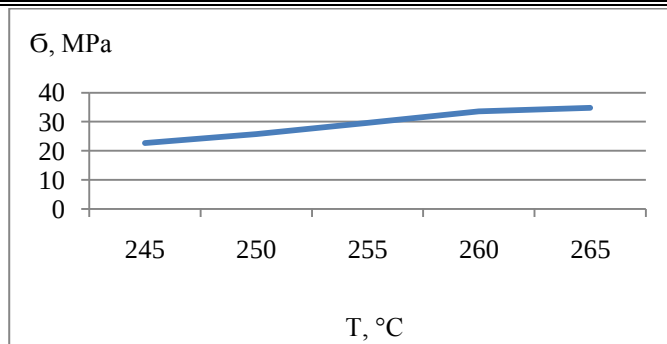


Fig. 2 - Dependence of the uniaxial tensile strength of samples based on PA6 obtained by FDM printing technology, on the print temperature

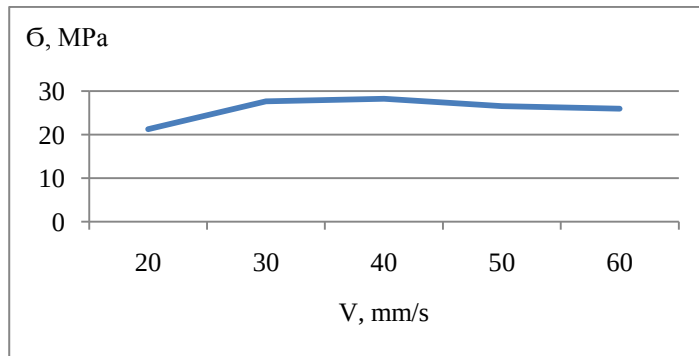


Fig. 3 – Dependence of the uniaxial tensile strength of samples based on PA6 obtained by FDM printing technology, on the print speed

It can be assumed that the strength characteristics of polymer products based on PA6 obtained by FDM technology are also dependent on their size (the area of the printed layers).

To evaluate this assumption, standard samples were printed in the form of Type 1 blades with a circulation of 1 to 5 products printed simultaneously in layers. It should be noted that an increase in the time of subsequent overlapping of the printed layer with PA6 melt at a printing speed of 40 mm / s over 200 s (Fig. 4, circulation of 3 products or more) leads to a noticeable decrease in the tensile strength of the samples. This, in turn, also requires a detailed examination of the identified dependence.

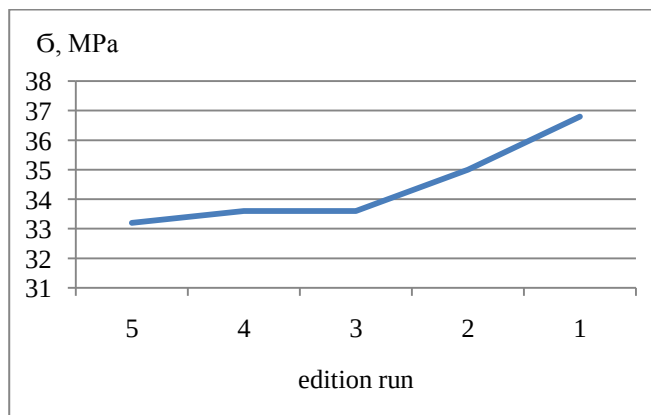


Fig. 4. Dependence of uniaxial tensile strength of samples based on PA6 obtained by FDM printing technology on the number of simultaneously printed products

4. Conclusion

To increase interfacial interaction in polymer composite systems, the facts of the effective use of finely dispersed detonation-carbon synthesis modifiers are known [8], which provide an increase in impact strength (at least 30%) when their content is in the range of 0.05–0.1 mass%. In addition, the introduction of compatibilizers into the composition of thermodynamically incompatible mixtures of the "polyamide-polyolefin" type provides an optimal combination of the deformation-strength and technological characteristics of composites based on aliphatic polyamides. Obviously, the solution to the problems of using polyamide filament to obtain high-quality products using FDM technology should be carried out with the involvement of voiced experience. The use of a copolymer of ethylene and vinyl acetate (SEVA) in amounts of 5..10 wt.% to increase the compatibility of PA6-HDPE mixtures does not provide the expected compatibilizing effect due to the course of oxidation processes characteristic of SEVA at temperatures above 150 ° C and requires additional administration thermostabilizers [10].

Thus, when determining the technological parameters of 3D printing of polymer products using FDM technology, it should be taken into account that engineering products based on PA6 along with accuracy criteria also require taking into account the manifestation of interlayer autohesion, the nature of which is determined by various printing parameters, the main of which are print temperature , print layer thickness and printable area.

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Use of virtual casting for optimization the density of complex geometric aluminum parts, casted in to 3D-printed sand foundry molds

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Abstract: The combined application in a foundry practice of 3D-printing, computer optimization through a virtual casting and modern visualization, by color scales and comparisons allows to be obtained details free of defects from the very first casting. One specific example for a fast optimized casting of a crankcase of aluminum alloy for a turbocharger is shown. The geometry of the detail is of high complexity, developed internal cavities and various wall thicknesses. With the use of three advanced software products, the time to reach the above goal is shortened by about two months and the minimum density in a critical point is increased almost 3 times.

Keywords: ALUMINUM ALLOY, DENSITY, SOUNDNESS, 3D PRINTED SAND MOLD, 3D PRINTED SAND CASTING SEGMENTS

1. Introduction

In order to avoid expensive adjusting experiments in the development of new foundry technologies, the use of methods for optimization by virtual casting [1, 2, 3] is innovative. This is even more true in case of casting in 3D-printed forms. In the new processes for 3D-printing of sand segments [4,5], including foundry cores and moulds, foundry slopes are not necessary. Such technologies are used in one-off and small series production of complex-geometric castings, in which 3D-printed elements are expensive, but without any alternative, to quickly create, with the necessary precision and dimensional accuracy the required form of the casted article.

2. Parameters and calculations

The goal of the work is to make an optimization by virtual casting in order to avoid or reduce possible density defects in the casting.

The subject of the survey is a turbocharger housing, the view of which (after machining and assembly of components) is shown in Fig. 1 (a). The complexity of geometry is obvious from the incisions made in two different sections. The aluminum casting of the housing is shown on FIG. 1b. The arrow in the figure indicates the location of the defect for optimisation, and the scale on the right is an automatic scale on which the minimum value corresponds (by color and location) to the lowest calculated density in the casting. The place where there is a risk of the presence of a foundry defect according to the preliminary calculations is indicated by an arrow (intake, porosity leakage etc.). This type of defect is related to density [6].



Fig. 1 Aluminium Turbocharger Housing
(a)-general appearance and transverse incisions illustrating complexity;
(b)-View of the casting with the place and size of the defect

A more convenient representation of density in percentages for general analysis is selected, but in any case the applied rule is that the 100% density from the scale corresponds to the best density in an aluminum casting = 2.67 g/mm³.

The 29% value of 2.67 g / mm³ was not satisfactory. In this place, it is not possible to add a feed with a dead head. This surface has a complex geometry, requires a high smoothness (Ra > 6.5 µm), and no trace of "discontinuity" of the surface.

Improvement will be sought using the most accessible parameters:

- Casting temperature;
- Percentage of silicon.

In this case, a full factor experiment is used as one of the parameters is on 4 levels and the other on 3 levels.

If time is limited and the factors are numerous, "Sobolev" or other experimental plans can be applied, which reduces the number of calculated attempts, but also carries a certain risk of missing the "best result".

Table 1 represents the 12 values of applications full factor experiment in the studied ranges:

- Casting temperature – from 730 °C to 760 °C, on 4 levels at 10 °C;
- For the percentage of silicon-from 6.5% to 7.5%, at 3 levels in 1%.

The casting is carried out in the same parameters for each test, except for the casting temperatures [°C] and the silicon Si content [%] shown in Table 1.

Some of the more important constant parameters are:

- Sand-form temperature: 20 °C;
- Time to fill the casting: 11.5 sec.;
- The chemical composition: Cu = 0.03 [%], Fe [%] = 0.10 [%], Ti [%] = 0.12 [%], Sr [%] = 0.025 [%], Mn [%] < 0.0 [%], Zn [%] < 0.00 [%].

The 3D-printed sand forms are made according to [7]. Heat-physical parameters are used, specific to 3D-printed sand segments [8].

Optimization calculations were conducted with the "Start-sequence" tool of Magmasoft software 5.4.2

The calculated values specifically for each individual experience are presented in table 2.

Table 1-the temperature of casting and the percentage of silicon and table 2-The minimum density values (Soundness) calculated for each experiment.

Table 1

Optimization factors		
Exp. N°	Casting temperature T[°C]	Content of Si [%]
1	730	6.5
2	740	6.5
3	750	6.5
4	760	6.5
5	730	7.0
6	740	7.0
7	750	7.0
8	760	7.0
9	730	7.5
10	740	7.5
11	750	7.5
12	760	7.5

Table 2

Optimization parameter	
Exp. N°	Soundness [%]
1	49.15
2	35.00
3	70.16
4	31.99
5	78.64
6	69.24
7	59.64
8	89.71
9	70.41
10	88.74
11	88.40
12	80.04

2. Visual presentation of the results after optimization.

In optimization, density values from minimum-31.99% to maximum-89.71% were obtained. This means that only with the variation of these 2 factors within the studied limits, the density can be changed almost 3 times.

The two extreme values (lowest and highest minimum density) are shown schematically in Fig. 2a) and fig. 2 (b), on the same scale in both cases.

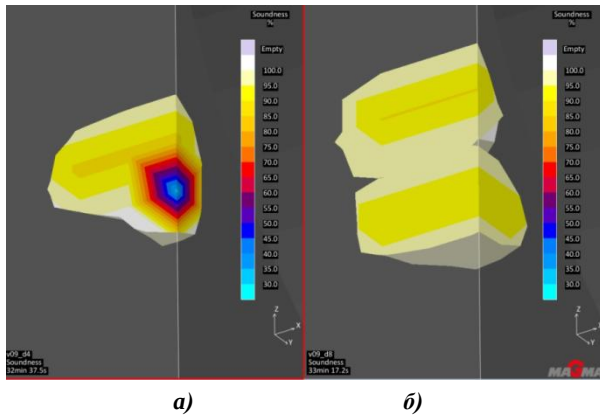


Fig. 2 Two of the results of the study area, mapped in the maximum transparency, the same incisions, the same three-dimensional scale and the same colour scale (30%-100%) In two cases:

- a)-the lowest value of the minimum density = soundness 31.99%,
- (b)-the highest value of the minimum density = soundness 89.71%.

From Fig.2 It is obvious that in both cases the critical zone is in the center, but while the abrupt density decrease of 100% to 31% is observed in Fig. 2a, the decrease in density is quite smooth between 100% and 89.71%.

3. Analysis of results and discussion

From the parallel coordinates diagram, it is obvious that very good results can be obtained in a sufficiently wide range of the two factors tested, T [°C] and Si [%].

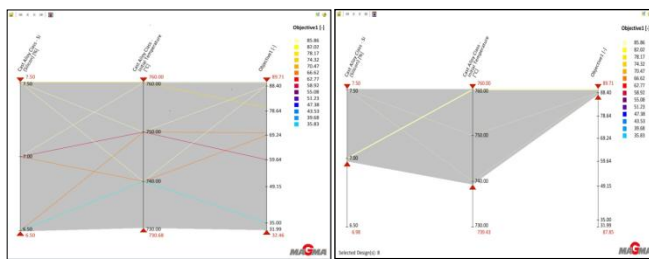


Fig.3 Presentation of optimisation results through parallel coordinates diagram

From the diagram of the private effects, it is obvious that the pouring temperature T [°C] in the research interval has no effect on the density of the critical zone. At the same time, the private effect of increasing the percentage of silicon is visibly large with a strong increase.

Accurate statistical confirmation of the described visual effects is given with the correlation matrix of Fig. 5 – Coefficient 0.75 for the silicon content against the minimum value 0.07 of the casting temperature coefficient.

4. Conclusions

1. Optimization through virtual casting gives an important and decisive contribution to the increasing application of modern 3D printed casting segments in the development of new technologies.

2. The application of virtual casting may be used in comparative research for scientific and applied development, where accurate quantitative measurements are required in the area without access for the installation of sensors.
3. Setting up new foundry technologies using 3D printer technologies by using virtual casting in parallel, displaying the results of the calculations in the most appropriate geometry and in the right colors, significantly reduces the time and the cost to achieve the correct result.
4. The results of measurements or calculations, shown at the exact point of the desired geometric shape, are the best way to be quickly and accurately understood by all those who wish to learn about them, in order to continue the prompt approach to the solve problem.

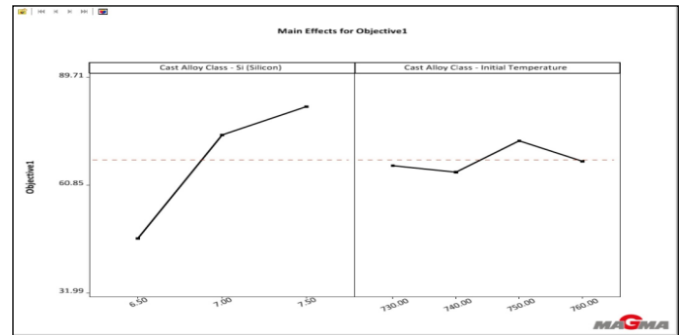


Fig. 4 Presentation of optimisation results through the private effects diagram

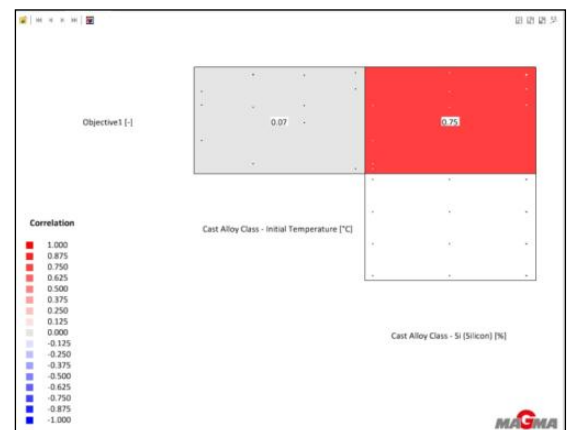


Fig. 5 Presentation of optimization results through the correlation matrix for quantification of the contribution of each of the independent factors

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Steels with bainite structure for railway wheels

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Abstract. Some wheel steels inclined for the self-quenching on bainite structure were produced and investigated after hot deformation and heat strengthening. Steels contained 0,12...0,45% of carbon, and also Si, Mn, Mo, Cr, Ni, V, Ti, Al. Steels with bainite structure after hot deformation and tempering were investigated. It was shown the possibility of the railway wheels production with bainite structure and hardness of 400HB without heat strengthening treatment. The results of investigation shown the possibility of railway wheels production with bainite structure, hardness of 400 HB and high complex of the mechanical and operating properties without heat strengthening treatment. These tasks solved owing to application of new wheel steels and up-to-date technology.

KEYWORDS: RAILWAY WHEELS, STEEL, BAINITE STRUCTURE, TREAD.

1. Introduction.

The increasing of thermocyclic load on the wheel during braking is one of main problem. Heat loads promote deformation in the wheel. Tread is heating by work of friction and some surface defects are formed. Complex approach for wear mechanism of railway wheels includes not only investigation of structural and corrosive changes happening in surface layers of wheel rims [1-13], but also analysis of wear particles and establishment of mechanism of their formation [14-21]. The variety of working conditions of friction pairs suggests that the general approach may be the idea of the fatigue nature of the destruction of the surface layers [22]. The problem of production of the highstrength and reliable railway wheels is very actual. This problem is compound and includes some aspects which connect with production of highquality steel, optimization of the each stage of forming, development of new design of wheels and also guarantee of essential level of heat strengthening. Modern conditions of operating of railway wheels needs the essential arrangements by the guarantee of high level of wheel rim up to 400 HB. At this time certain countries use the rails with hardness up to 450 HB and the bainite structure. At that, the ratio between hardness of wheel tread and rail should be as follows $(0.8...1.0) / 1.0$.

Traditional microstructure of wheel rim is dispersion perlite with small share of ferrite, that ensures sufficiently high complex of strength, hardness and toughness of wheel steel. But such microstructure even by the using of microalloying allows to have maximum hardness of 330 HB. It lets to suppose that possibilities of perlite structure in that senses were settled and new nontraditional approach is assential.

Perspective microstructure for the guarantee of correlation of high hardness, strength, toughness and wear resistance of steel is bainite [23,24]. It is known in advanced railway countries the researches by the development of bainite rails and railway wheels are conducted. Most of works by the development of bainite wheels were connected with task of production of steels with high resistance to the martensite transformation for reducing and even removing of probability of surface defects of fatigue.

The goal of this work was development of bainite steels with hardness up to 400 HB and high complex of mechanical and

operating properties. The investigations offer complex solution to ensure higher reliability and safety of railway wheels, in particular development and production of new railway wheels with sufficiently improved mechanical and service properties.

2. Materials and Procedures.

The research steels with low content of carbon (0,12...0,45%, mass) and different contents of Si, Mn, Mo, Cr, Ni, V, Ti, Al were produced. Castings were exposed to plastic deformation (1200...900 °C) with different degrees of deformation (50 and 90%) and cooled on the air. After hot deformation specimens were tempered (500...525 °C) for reduce of stresses.

Metallographical (optical and electron microscopes) and X-ray radoigraphical researches were made. Methods of testing: hardness, mechanical properties by tensile, fracture toughness, wear test. The resistance of steels for martensitic transformation during rapid heating and cooling by the Jomini end guenching was investigated

3. Results and discussion.

Microstructure of steel 1 after hot deformation was bainite with small part of martensite (about 5%). Degree of dispersity of structure rised with the increasing of deformation degree (Fig. 1, a, b). Needled bainite is twinned, it known else lath ferrite. Analysis of replicas shown that in regions of bainite the ultra disperse carbides Mo_2C and $(Fe, Cr)_3C$ present. Microstructure of steel 2 was ferrite-perlite. By degree of deformation 90% the ferrite banding was appeared that is admitted in the structure of wheel web. In this steel the structure of bainite in the time of cooling after hot deformation was not formed.

Microstructure of steel 2 was bainite-ferrite mixture with small quantity of the martensite. Bainite has lath type. Steels 4 and 5 had bainite structures with small part of martensite (up to 5%). Morphology of bainite was lath type close to upper bainite. In the bainite laths carbides VC, Mo_2C , $(Fe, Cr)_3C$ present, although there are the lathes without carbides (they close to lower bainite). Microstructure of steel 6 is ultra dispersed perlite with slim interlayers of ferrite

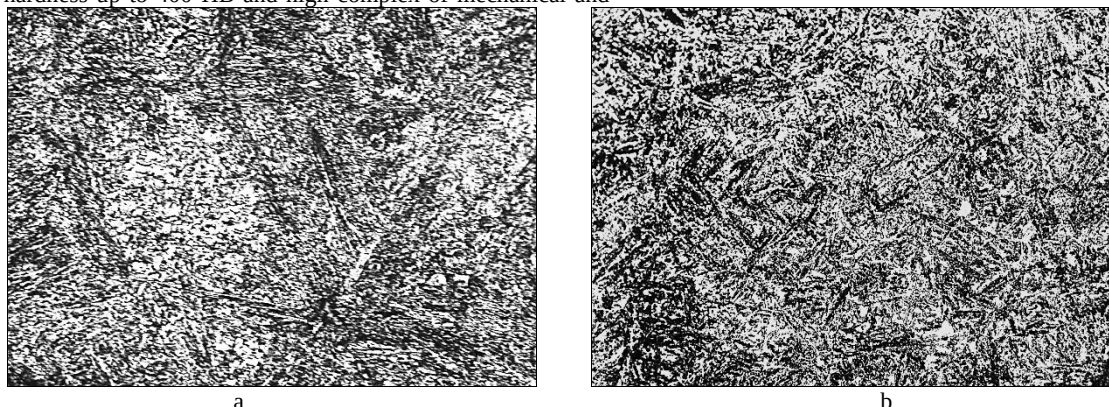


Fig.1. Microstructure of hot deformed steel 1: degree of deformation 50 (a) and 90% (b); x200

Therefore hot deformation resulted in dispersion of microstructures of cast steels, moreover than more degree of deformation Steels 1, 3, 4, 5 after hot deformation have microstructure of bainite with small part of martensite (up to 5%). Presence of martensite is caused for nature of bainitic transformation. Obviously during formation and growth of bainitic lathes (or needles, lamelles) the local redistribution of carbon and alloying elements changes the kinetics and mechanism of austenite decomposition. Therefore there is not microstructure of steel with 100% of bainite. Except bainite and martensite, disperse carbides of molybdenum, vanadium and alloying by chromium cementite present in microstructures of steels. Steels 1, 3, 4, 5 are the self-

quenched in the time of cooling after hot deformation. Bainite in these steels is different by morphology and degree of dispersity.

Electron microscopic investigations was shown that and upper, and low bainites have favourable lath structure with characteristic cellular dislocation substructure. Density of dislocation is about $10^{11} - 10^{12} \text{ cm}^{-2}$, which close to substructure of deformed metal (Fig. 2). This allows the possibility to admit that bainite in definite measure hereditates the deformation substructure. Degree of hot deformation influence on the degree of dispersity of bainite and cellular dislocation substructure. Analysis of fine structure of martensitic regions was shown that in martensite at the temperature of bainitic transformation self-tempering passed and because martensite will not call the brittleness of steel.

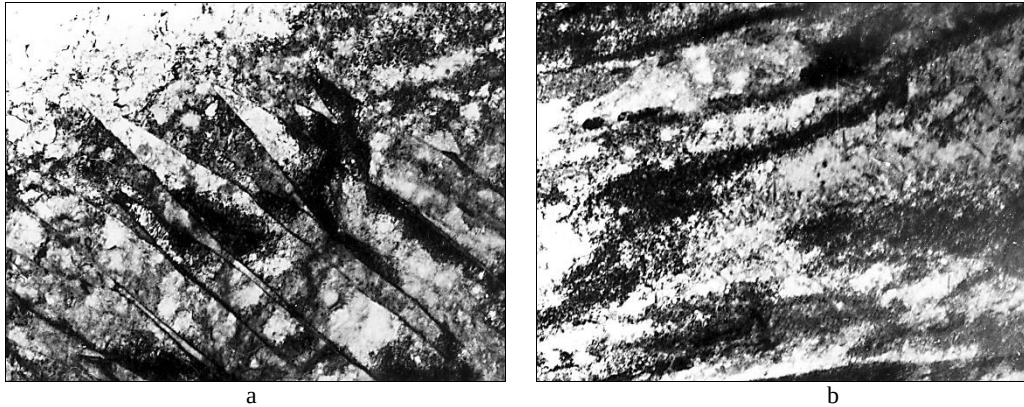


Fig.2. Fine structure of bainite in hot deformed steels 1 (a) and 4 (b); degree of deformation 50%; $\times 22000$

System of alloying of steel influence on the position of critical points on diagram equilibrium Fe-C and therefore influence on the morphology of α -phase and carbides in bainitic structure. In upper bainite (without carbide) the considerable part of carbon, which did not diffuse to surrounded austenite during growth of laths of bainite, forms Cottrell atmospheres on the dislocations. Remnant

of carbon is spent on the carbides and martensite formation. Upper bainite does not need tempering, therefore it is the favourable structure from point of view of strength, plastic and tough properties correlation.

In table 1 the parameters of fine structure of steels after hot deformation are shown.

Table 1. Parameters of fine structure of bainite after hot deformation (D_{hkl} – size of blocks, $\Delta a/a$ – microstresses, ρ_L – density of dislocations)

Treatment	steel 1			steel 3			steel 4		
	$D_{HKL} \cdot 10^{-4} \text{ cm}$	$\Delta a/a \cdot 10^{-3}$	$\rho_L, \text{ cm}^{-2}$	$D_{HKL} \cdot 10^{-4} \text{ cm}$	$\Delta a/a \cdot 10^{-3}$	$\rho_L, \text{ cm}^{-2}$	$D_{HKL} \cdot 10^{-4} \text{ cm}$	$\Delta a/a \cdot 10^{-3}$	$\rho_L, \text{ cm}^{-2}$
Hot deformation ($\epsilon = 50 \%$)	4,4	2,32	$7 \cdot 10^{12}$	3,9	-	$4,5 \cdot 10^{11}$	3,0	0,45	$2,6 \cdot 10^{12}$
Hot deformation ($\epsilon = 50 \%$) + tempering	4,5	2,24	$6,5 \cdot 10^{11}$	4,8	-	$6,9 \cdot 10^{10}$	2,7	0,21	$5,0 \cdot 10^{11}$

After tempering the level of microstresses in all steels is reduced. Meanings of dislocation density confirm the results of electron microscopic investigations. After tempering the density of

dislocations reduces on the order. The quantity of retained austenite was 5...10 %.

After hot deformation the hardness of steels was defined (table 2).

Tabl. 2. Hardness of steels (HB) after hot deformation and tempering

steel	Condition of steel			
	Hot deformation $\epsilon 50 \%$	Hot deformation $\epsilon 90 \%$	Hot deformation $\epsilon 50 \% + \text{tempering}$	Hot deformation $\epsilon 90 \% + \text{tempering}$
1	405	420	432	455
2	190	264	195	250
3	408	410	402	409
4	420	424	437	451
5	400	401	409	432
6	338	475	363	434

Steels 1,3,4,5 with bainite microstructure have hardness 400...455 HB after hot deformation or deformation and tempering. It is important that bainitic structure in hot deformed steels was formed without special heat treatment. That allows to affirm that essential level of hardness of railway wheel rims may be provided after hot deformation without heat strengthening quenching. But it

is essentially also to define the level of the mechanical properties and resistance of steels to the martensitic transformation during heat of tread of railway wheel.

The complex of the new wheel steels characteristics was as follows (Table 3)

Tabl. 3. Mechanical and operation properties of bainitic steels and standard wheel steel*

	Hardness, HB	Ultimate strength, MPa	Yield point, MPa	Percent elongation, %	Percent reduction, %	KCU, J/sm ²
after hot deformation	400...435	1309...1610	1044...1318	7,8...13,2	8,2...28,5	15,61... 41,8
Standard wheel steel after heat strengthening	248 255	900...1100 930...1130	- -	12 8	21 14	3,0 2,0
Improvement the resistance against wear and tear to 1.2-1.4 times						
In a situation of sharp brake in the operation period this structure can guaranty the high resistance against the thermo impact						

*Tested in Institute of Ferrous Metallurgy NAS of Ukraine

Properties of bainite steels are better than properties of standard wheel steel with perlite structure.

During operation of railway wheel the tread is exposed to heat and mechanical loads, which promote the accumulation of heat and mechanical fatigue, wear of tread and flange, plastic shears in the slim surface layer, appearance of some defects which are caused by formation of martensite near tread (Fig. 3). These defects are formed in conditions of abrupt braking, when thin surface layer of tread is heated up to temperature of austenite area (upper 800°C) by friction from abrupt action of the brake block. Deformation of this thin layer in the plastic austenite condition takes place, but it can not endure a big operating load, then tread abruptly cooling in the

time of disengagement of brakes and this leads to formation of the "white layer". It is known "white layer" represents ultra dispersed martensite (gardenite), which has high brittleness, especially by the blows of wheel against the butts of rails (that is by dynamic load). Moreover, it promotes formation of some defects in the areas of heat action and this lead to increase of quantity of metal which is removed by the turning in the process of tread profile restoring.

For comparison the specimens of standard wheel steel and experimental steels 1, 3, 4, 5, 6 were exposed to heating in the austenite area by the Jomini end quenching.

The results of microhardness measuring are shown in table

4.

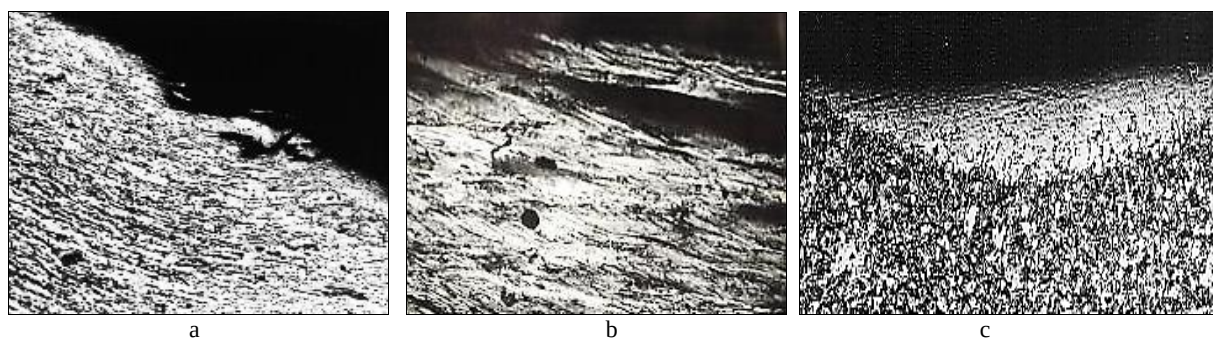


Fig.3. Structure of railway wheel tread after operating, x200

Tabl. 4. Microhardness (HV) along length of specimens

Steel	Place of measuring from the end of specimen, mm						
	0	2	4	6	8	10	12
Standard wheel steel	640	640	625	500	320	250	250
1	400	400	400	400	390	380	380
3	420	445	430	420	420	370	380
4	450	460	470	440	460	430	430
5	460	470	450	440	450	435	430
6	600	600	590	590	580	575	570

Standard wheel steel and steel 6 have inclining to the martensitic transformation. Steels 1, 3, 4, 5 showed stable values of microhardness with the level of bainite microstructure, and this was confirmed also by the metallographical research of these specimens. Of course, it is not possible to expel the possibility of formation of sliders and dynamic loads connected with sliders in the wheels from bainite steel. But advantages of the bainite wheels are evidently in this problem by the comparison with wheels from standard steel.

4. Conclusions.

The results of investigation shown the possibility of railway wheels production with bainite structure, hardness of 400 HB and high complex of the mechanical and operating properties without heat strengthening treatment. These tasks solved owing to application of new wheel steels and up-to-date technology.

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Properties of composites with nanodiamonds of detonation synthesis

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Abstract: Modern metals, alloys and polymers, using in mechanical engineering, now have such high-temperature and strength properties that do not meet the advanced requirements. One of the methods to improve their physico-mechanical properties is the method of hardening by dispersed additives. Nanodiamond (ND) and diamond-carbon -containing material (NDC) of detonation synthesis, having nano-structure and high surface energy, impact structurally on any materials contacting with them. Detonation synthesis is a fundamentally new and productive type of basic technology for producing nanostructures and nanomaterials. ND of detonation synthesis is a unique material that combines the properties of diamonds and the advantages of nanostructures. Industrial development of the given method made it possible to actually reach large-volume production and consumption of ND in a number of industries. The effectiveness application of ND and NDC in industrial lubricants, polishing, composite galvano-chemical coatings, metal and polymer-based composites has been shown.

Keywords: NANODIAMOND, DIAMOND CARBON MATERIAL, POLYMER COMPOSITES, METAL-DIAMOND COATINGS, MICRO HARDNESS, WEAR AND TEAR, LUBRICANTS, POLISHING MATERIALS

1. Introduction

Artificial diamonds are considered to be strategic materials all over the world, as they play a vital role in the development of the industry. With the establishment of a new detonation method for the synthesis of diamonds, there appeared fundamentally new opportunities for the implementation of advanced technologies [1,2]. The synthesis is carried out by detonation of explosives in an explosion chamber, while nanocarbon (NDC) and nanodiamonds (ND) are formed in condensed detonation products with a high mass yield [3,4]. The diamonds are generated from explosives by chemical reactions under rather non-equilibrium conditions, whereupon their structure becomes defective and the particle size is small. The average size of the diamond microcrystallites is between 4 and 6 nm, and the specific surface area of the powders ranges between 300 and 400 m²/g [5].

Possessing nanoscale and high surface energy, diamonds have a structural and dispersion-strengthening effect being in contact with any materials. By morphology, microstructure, element composition, and reactivity, NDC and ND are close to each other. Therefore, as products of detonation synthesis, NDC powders themselves can be attractive both scientifically and practically.

NDC and ND is currently applied as anti-friction additives to motor, industrial oils and greases; in pastes and suspensions for super finishing material polishing; in wear-resistant electrochemical and chemical metal-diamond coatings; as dispersion-strengthening additives in composite materials based on polymers, metals, alloys and rubbers; as effective sorbents, catalyst carriers, biomarkers, transporter of medicinal substances and etc. [6].

In this work, the properties of composites with nanodiamonds of detonation synthesis are presented.

2. Industrial lubricants

Figure 1 shows the comparative results of research into the tribotechnical characteristics of oil at various loads (P) in the friction zone. Compared to pure oil, a NDC additive reduces the friction coefficient (f) and, consequently, the oil temperature (T) in the friction and pad wear (I) zone. In addition, the limit load increases by three times. Concentrated carbon properties such as the nano size and round shape of particles, adsorption, and sedimentary stability in oil suspensions fully manifest themselves here. Solid particles with an oil film on their surface to avoid dry friction are always present in the friction zone. Therefore, this effect reached in all lubricants: motor and technological oils; plastic and hard lubricant.

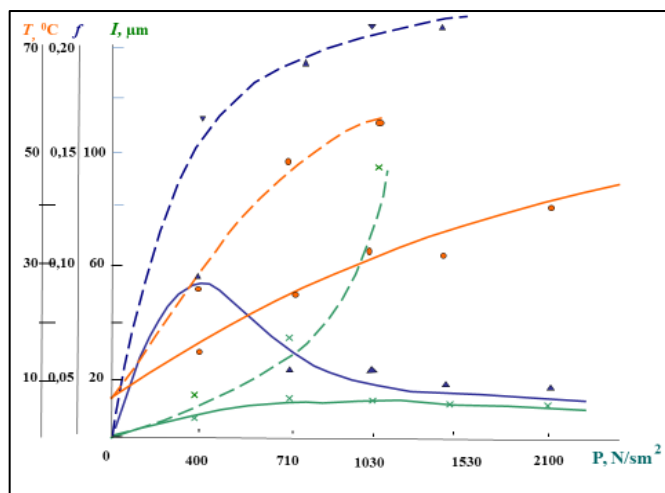
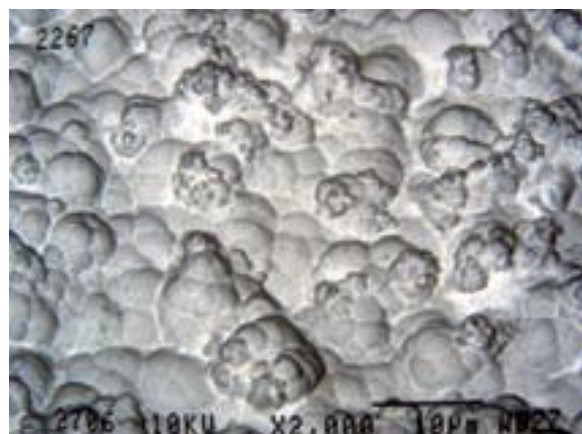


Fig. 1 Tribotechnical characteristics of industrial oil. Dotted lines for pure oil, solid lines for oil with an addition of 0.1% NDC.

3. Composite galvano-chemical coatings

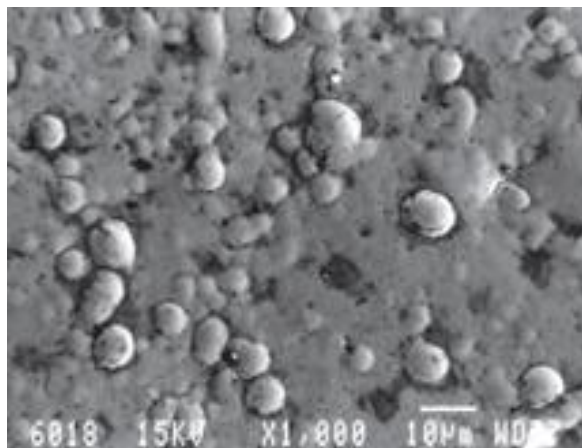
Nanodiamond properties such as resistance to acidic media and sedimentary stability made it possible to improve the properties of composite coatings produced by chemical and electrochemical deposition of metal films. As ND are introduced into the process for various metals, the same picture is observable: the grain size decreases (fig. 2,3), the micro hardness increases, and the wear resistance of coatings is improved (table 1).



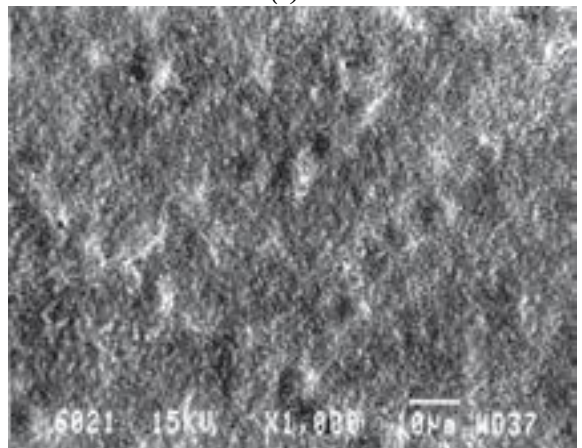
(a)



Fig. 2. Microstructure of electrochemical coating of chromium (a) and chromium with ND (b)



(a)



(b)

Fig. 3. Microstructure of chemical coating of nickel (a) and nickel with ND (b)

Wear reduction cannot be explained only by *ND* inclusion, since the *ND* content in a coating, for example, electrochemical nickel, does not exceed 1.5% and in a chromic coating it does not exceed 0.05%. Thanks to their surplus surface energy, *ND* have a structuring effect on deposited metal films, reducing the grain size and disordering the chromium structure to the limit at maximum micro hardness values. The use of this effect in industrial technology has confirmed the efficiency of metal-diamond coatings at 200 factories Russian. This technology is used company by Armoloy, USA. The implementation of the process does not require the remodeling of electroplating equipment, since the electrolyte is modified by adding an *ND* aquatic suspension to the initial plating tank.

Table 1. *ND* electrolyte additive effect on various metal sediment properties

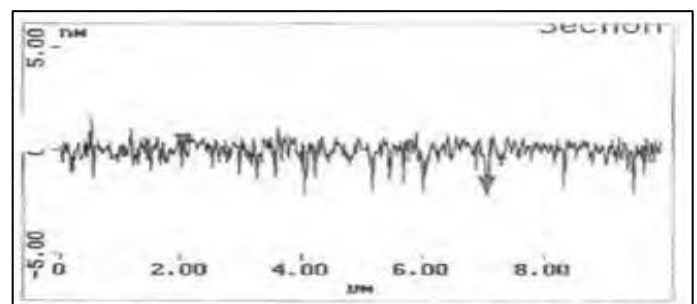
Sediment type	ND in electrolyte, g/l	Micro hardness, GPa		Wear resistance increase, times
		Initial	with ND	
Chromium electrochemical	13,0÷15,0	9,8÷11,1	13,2÷14,6	3.0 ÷4.0
Nickel electrochemical	9,5÷10,5	2,8÷3,0	4,6÷5,8	2.4 ÷4.2
Copper electrochemical	5,0÷10,0	2,0÷2,1	3,2÷3,3	4,8 ÷7,0
Cobalt–phosphorus electro chemical	0,5÷2,0	5,0÷5,25	6,8÷7,0	3,6 ÷4,1
Copper chemical	2,0÷6,0	1,9÷2,1	6,4÷6,6	-
Nickel chemical	4.5÷5.5	4,2÷4,4	6,1÷6,3	3,7 ÷4,0

4. Composite material for super-finish polishing

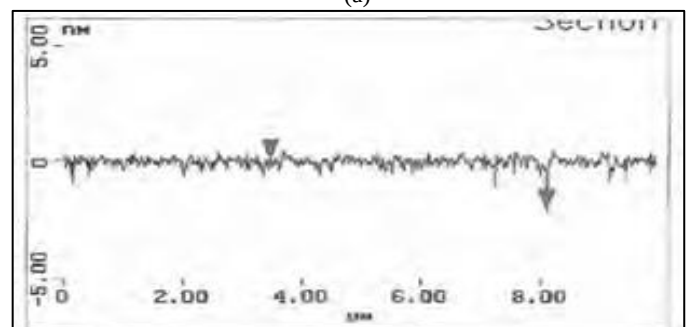
Polishing is a traditional sphere of diamond application. The best polishing abrasives have particle sizes no less than 0.1 μm . Thanks to its homogeneous granulomeres size composition, *ND* as the finest abrasive has turned out to be indispensable for super finish polishing. Nanodiamond suspensions and pastes allow surface finishes of several angstroms (table 2, fig. 4), which is an order of magnitude higher than the best international results in this sphere.

Table 2. Results of the polishing. Suspension ND (4%) in ethyleneglycoles.

Material	Roughness (Ra), nm
Hard alloy	1÷5
Steel; Sapphire	5÷6
Quartz; Silicon	0,5÷1,5
Molten silicon oxide	0,5÷1,0
NaCl; KBr crystal	2÷3



(a)



(b)

Fig. 4. Roughness of silicon plate before polishing (a) and after (b) Multi-level ND particle aggregation involves a specific polishing mechanism. The impact of the polishing system (ND-carrier) on the treated surface on the one hand is mitigated, and on the other is intensified by the generation of new diamond surfaces. ND is effective where the main result of the polishing process is a surface frequency class, not performance.

5. Composites

Nanodiamonds with developed surfaces and high surface energy have dispersion strengthening and structuring effects on any material that contacts them. Dispersion strengthening can explain the proper ties of metals and polymers with ND additives. Thus, the micro hardness of aluminum samples improves as the ND content increases (table 3), approaching that of low-grade steels but still preserving the advantages of a light metal. The wear resistance of aluminum compacts increases by 1.3 times from 2% ND, and from 10% to 1.8 times. Similar results were obtained when ND was introduced into magneto-uggy amorphous alloys used in magnetic heads of digital magnetic recording systems.

The wear resistance of fluoroplastic (Teflon) approaches bronze in wear resistance (table 4), and the friction coefficient is preserved at the level of pure fluoroplastic. In terms of the degree of impact in comparison with known dispersed additives, NDC takes the leading place (table.5).

The performance of polyamide samples with a 0.5% ND supplement is maintained when the maximum load increases from 20 to 150 kg/cm². Increased strength and wear resistance are also obtained on polyacrylamide, polymethylmethacrylate, polyethylene.

Table 3. Aluminum composite with ND*. Characteristics

ND content, %	Micro hardness, GPa	Density, g/cm ³	Porosity, %	Thermal conductivity, W/(m K)
0	0,76	2,73	0	162
2,5	1,81	2,71	0,5	141
10	1,97	2,69	1,1	101
20	2,68	2,71	1,9	64
50	5,22	2,6	1,5	9,2

* Hot pressing at temperature 793-803K and pressure 1,0 GPa

Table 4. Fluoroplastic composite* with coal powder and NDC. Characteristics

Additive, %	Compressive modulus, MPa	Friction coefficient	Wear resistance increase, times
Without additive	4,2	0,21	1,0
Coal powder, 20 %	11,5	0,32	25,0
NDC, 5 %	4,9	0,21	70,0

* Hot pressing at temperature 643K

Rupture strength of composite plastic made of fiber glass filament and binder on the basis of epoxy resin increases with 1.0% additive by 1.3 times for NDC and by 1.5 times for ND. Moreover, carbon nano-additives effectively influence on crack resistance of the composite.

In rubbers, NDC has a structuring effect already at 0.5%, increasing the vulcanization rate by 1.3 times. The best results were obtained at NDC doses of 1-3 phr. Within this range, we observe the growth of indicators such as wear resistance (2.5-4.5 times), gap resistance (1.3-1.4 times), conditional strength at rupture (1.1-

1.2 times), and (very importantly), elasticity; other indicators remain unchanged.

Table 5. Wear resistance of Fluoroplastic with different additives

Additive (5%)	Surface area (additive), m ² /g	Surface wear area, mm ²
NDC	344	7,2
NDC	468	5,9
ND	282	10,6
SiO ₂	400	19,0
Si ₃ N ₄	28	13,7
Co[Al ₂ O ₄]	10	17,5
Soot	15	19,7
Graphite	10	28,2
MoS ₂	0,2	28

Bench and performance tests show that industrial rubber parts last 1.3-2 times of their guideline life; tires last 1.3 times of their standard run.

6. Conclusion

ND of detonation synthesis is a unique material that combines the properties of diamonds and the advantages of nanostructures. Possessing nanoscale and high surface energy, diamonds have a structural and dispersion-strengthening effect being in contact with any materials. The effectiveness application of ND and NDC in industrial lubricants, polishing, composite galvano-chemical coatings, metal and polymer-based composites has been shown. Currently, the detonation method allows to receive ND with grain size 60-90 nm [7]. Their use will increase the range of composites with new properties.

Acknowledgments

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