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SYNTHESIS OF KINEMATICAL CONJUGATE SPATIAL GEARING

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Abstract: This study contains main views and scientific principles of its authors, used as a basis for mathematical modeling, oriented to the synthesis of kinematically conjugated spatial (hyperboloid) gear drives.

Keywords: SPATIAL GEARING, HYPERBOLOID GEAR DRIVES, KINEMATIC SYNTHESIS, MATHEMATICAL MODELLING

1. Introduction

The main stage of the mechanical systems' design, an object of the *Applied Mechanics* and *Theory of Mechanisms*, is known under the name *Synthesis of Mechanisms*. In the most common case, the synthesis of mechanisms involves the following two general tasks [1, 2]:

- Choice of a structure of the designed mechanism by realizing a structural synthesis.
- Design of the chosen kinematic scheme of the mechanism. This task is known as a *kinematic synthesis of the mechanism*. Through its solution it is possible to determine the constant geometric parameters of the chosen structure of the mechanism, such to satisfy its preliminary defined kinematic characteristics, like the function of the law of motions transformation.

In case of the synthesis of spatial (hyperboloid) gears, the task of structural synthesis is not solved, since the spatial transformation of rotations is realized, as a rule, by three-link mechanisms with high kinematic joints.

Obviously, when it is talked about synthesis of gear mechanisms, it should be understood that *the task of kinematic synthesis has to be solved*. As for all mechanical systems and spatial gear mechanisms as well, the results of solution of the mentioned task have to provide to the designer an optimal amount of information in order to ensure the realization of the next stages of gear sets' design: (1) development of the design project of the gear drive, which determines a specific structural form of the mechanism, ensuring its strength, reliability, durability, optimal efficiency and etc.; (2) technological preparation of processes related to the production, providing the planned technical and economic indicators of the synthesized mechanics.

The work realizes studies on conjugated hyperboloid gear sets with linear tooth contact oriented to their kinematic synthesis.

2. Mathematical Modelling for the Synthesis

The main purpose of each transmission mechanism is to realize with a necessary exactness a preliminary defined law of motions transformation. Among the group of gear mechanisms, spatial three-links gear drives, transforming rotations between crossed axes, are essential for both industry and transport. The reason for this is that they are characterized by the presence of large number of free parameters and to search for suitable combinations among them creates the opportunity, in the synthesis of the considered type mechanisms, the desired exploitation characteristics to be obtained, such as: high reliability and durability; low vibrational activity and noiseless; high accuracy in realization of the motions transformation law, high hydrodynamic loading capacity, etc. As a rule, the positive technological and exploitation features of the spatial gear mechanisms are result from higher requirements to obtain their specific kinematic characteristics. All this determines a kinematic character of the approach to the synthesis, and respectively *kinematic character of the created mathematical models*.

The successful implementation of spatial gear drives with new kinematics and strength characteristics into industry is retained by the absence of defined adequate approaches to the mathematical modeling, oriented towards their synthesis and design. In their studies over the years, the authors of this work have offered two approaches for creation of a mathematical model for synthesis [2]: *upon a pitch contact point and upon a region of mesh*.

2.1. Mathematical Modeling for the Synthesis upon a Pitch Contact Point

It is based on the assumption that all the necessary quality characteristics, defining concrete exploitation and technological requirements to the active tooth surfaces are guaranteed for only one contact point P (respectively and for its close vicinity) of the active tooth surfaces Σ_1 and Σ_2 (see Fig. 1) [2]. This model is applicable to the synthesis of spatial gear mechanisms with both point and linear contact. According to it, the common contact point P of the conjugated tooth surfaces Σ_1 and Σ_2 is a common contact point of the circles H_i^c ($i = 1, 2$), called *pitch circles* ($H_1^c : H_2^c$) i.e., *point P is the pitch contact point*. The tangent plane T_m , which includes tangents to H_i^c ($i = 1, 2$) at point P is a pitch plane, and $m - m$ is the pitch normal to the T_m at point P . In Fig. 1 a case of mutual placement of pitch circles in the fixed space, corresponding to the traditional constructions of hyperboloid gear mechanisms with externally meshed tooth surfaces is illustrated. The diameters d_i ($i = 1, 2$) of H_i^c ($i = 1, 2$), together with the parameters a_i , θ_i , δ_i ($i = 1, 2$), δ and a_w determines the type of the construction and its dimensions, shape, and mutual position of the movable links in the fixed space (in the coordinate systems $S_i(O_i, x_i, y_i, z_i)$, ($i = 1, 2$)). At the same time, these dimensions are related to the definition of the longitudinal and cross orientation of the active tooth surfaces Σ_i ($i = 1, 2$) at the pitch contact point.

In other words, the pair of circles ($H_1^c : H_2^c$) has a direct relation to determining the pitch of the teeth and, respectively, the tooth module of the designed gear system. The parameters d_i , δ_i ($i = 1, 2$) are the defining dimensions of the reference coaxial rotation surfaces, i. e. the overall dimensions of the blanks of the gears depend on them.

The parameters, mentioned above, are also used in determining the dimensions of the mounting of the synthesized gear mechanism.

From the above, it follows that the mathematical model for synthesis upon a pitch contact point ensures an algorithmic solution of two basic problems:

- Synthesis of the pitch configurations [2-4];

- Synthesis of the active tooth surfaces [3, 4].

The necessary (preliminary defined) geometric characteristics of the synthesized gear mechanism in a close vicinity of the pitch contact point are found by solving these two problems together.

In conclusion, it should be pointed out, that the described here approach to synthesis of spatial gears is based on the following kinematical condition: *The relative velocity vector $\bar{V}_{12} = \bar{V}_1 - \bar{V}_2$ ($\bar{V}_i$ is a circumferential velocity of the link i at point P) at the pitch contact point P has to lie both in the pitch plane T_m and in the common tangent plane T_n of the tooth surfaces Σ_1 and Σ_2 contacting at P , and this vector has to be oriented along the common tangent to the longitudinal lines of the active tooth surfaces Σ_i ($i = 1, 2$).*

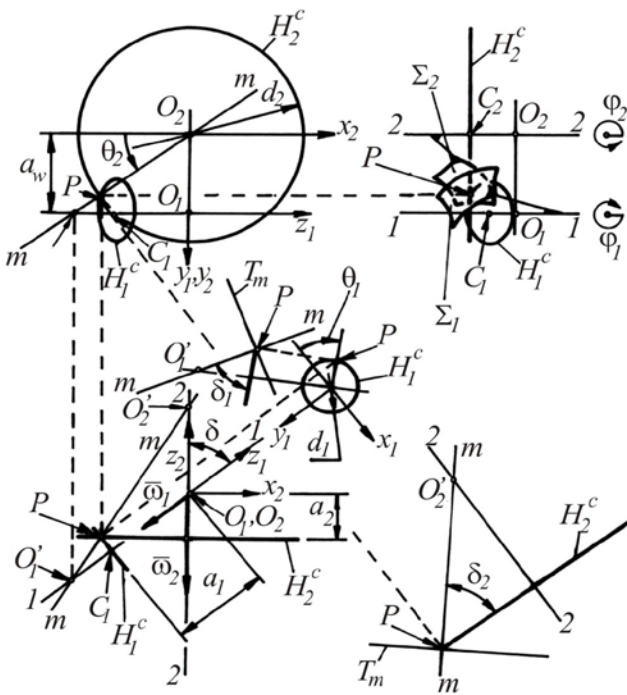


Fig. 1 Geometric and kinematic interpretation of the mathematical model for synthesis based on a pitch contact point: H_i^c ($i = 1, 2$) - pitch circles; T_m - pitch plane; $m - m$ - pitch normal to T_m at point P ; Σ_i ($i = 1, 2$) - tooth surfaces, contacting at the point P

It has to be noted that the considered approach for the basic synthesis upon on a pitch contact point is described by the fact that the created mathematical model and the worked out on it algorithm are characterized with a **universal structure** for all types of hyperboloid gear sets. The universalization of the algorithm can be continued and at a certain stage it can be transformed into an optimization synthesis' algorithm by constructing criteria for control of the quality of meshing in a vicinity of the pitch contact point.

When the briefly described approach for the synthesis is applied, then a mathematical model for synthesis of Spiroid gear sets [5] is elaborated. On its bases is elaborated a computer program for their optimization synthesis and design (see Fig. 2) [2].

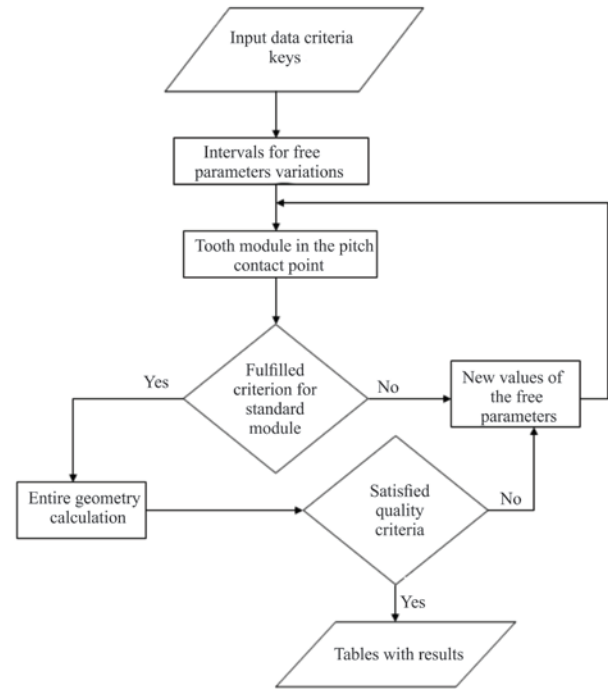


Fig. 2 Program scheme for an optimization synthesis of a Spiroid gear pair

2.2. Mathematical Modelling upon Region of Mesh

When hyperboloid gear sets with a linear contact between the tooth surfaces are synthesized, it is obvious that it is necessary to control the quality of meshing characteristics over the entire region of mesh or in a certain area for a specific reason. Such an approach to the task for the synthesis requires the construction of an adequate mathematical model. Its general kinematic scheme is shown in Fig. 2 [2].

Mathematical modelling for synthesis upon mesh region is **not a structurally universal**. The reason for this is that the concrete geometric and kinematic characteristics of the mesh region depend on its placement in the fixed space, as well as on the geometric characteristics of the instrumental tooth surfaces Σ_j , that generate the active tooth surfaces Σ_i ($i = 1, 2$).

This mathematical model is suitable for application when:

- It is not possible to define the pitch circles, respectively the pitch contact point;
- the condition for the special orientation of the longitudinal lines of the synthesized tooth surfaces is not mandatory or cannot be kept;
- the specific technological requirements has to be kept (for example, when the same tool is used in the manufacturing of gear sets, that realize different gear ratios, but based on the same size blanks for the gear sets, housing details and etc.).

In the basis of the mathematical modelling for synthesis of spatial gear drives upon mesh region is the kinematic model of surface of action /mesh region. Following this approach, we will note that the optimization process, in its essence, is a determination of both the optimal geometry and limitations on the mesh region, as part of the action surface (Fig. 3).

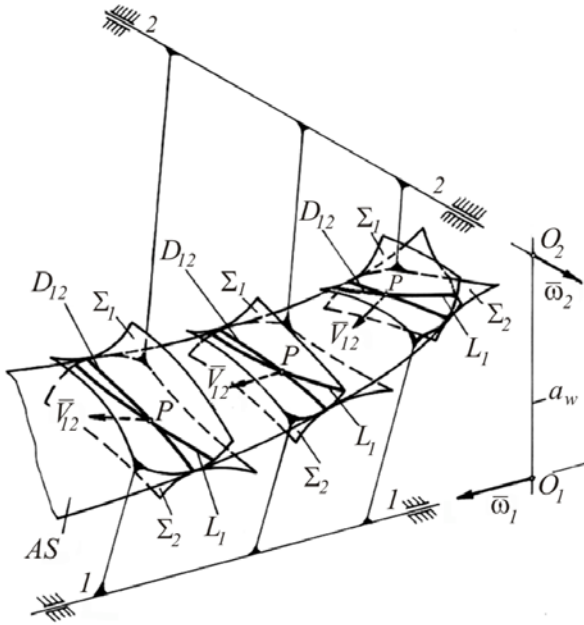


Fig. 3. Geometric-kinematic interpretation of the model for synthesis upon mesh region: L_1 - longitudinal line of Σ_1 ; D_{12} - contact line between Σ_1 and Σ_2 ; AS - action surface

As it has already been noted, when the spatial gear pair with a linear contact is synthesized, it is necessary to control their quality characteristics in the whole mesh region. The technology of the tooth surfaces generation of these class gear mechanisms is based on the second principle of T. Olivier. For this reason, the action surface of every gear drive is defined through the active tooth surfaces of one of the movable links of the three-link hyperboloid gear mechanism.

In order to illustrate this approach to the mathematical modelling, let us accept that Σ_1 - the active tooth surface of one of the movable links ($i = 1$ - pinion), is known. Let it be presented by its vector equation:

$$\bar{\rho}_{1,p} = \bar{\rho}_{1,p}(u, \vartheta), \quad (1)$$

where $\bar{\rho}_{1,p}$ is a radius-vector of Σ_1 in the coordinate system $S_p(O_p, x_p, y_p, z_p)$, fixed to the pinion; u, ϑ - parameters of Σ_1 .

The equation (1) also describes the generating tooth surfaces Σ_2 of the second movable link ($i = 2$), instrumental surfaces $\Sigma_j \equiv \Sigma_1$. Let's accept that on Σ_1 are no folds and interruptions, i.e. of this surfaces the following condition is accomplished:

$$\bar{n}_{1,p} = \frac{\partial \bar{\rho}_{1,p}}{\partial u} \times \frac{\partial \bar{\rho}_{1,p}}{\partial \vartheta} \neq \bar{0}. \quad (2)$$

Here $\bar{n}_{1,p}$ is a normal vector in an arbitrary point of Σ_1 .

In accordance with the kinematic approach to the synthesis, through the direct application of the basic theorem of meshing [2-4], the contact lines on the active tooth surface Σ_1 can be defined, i.e.

$$\bar{\rho}_{1,p} = \bar{\rho}_{1,p}(u, \vartheta), \quad \bar{n}_{1,p} \cdot \bar{V}_{12,p} = 0, \quad (3)$$

where $\bar{V}_{12,p}$ is a relative velocity vector in an arbitrary contact point.

When the equation systems (3) is written in the fixed coordinate system $S(O, x, y, z)$, then the mesh region is obtained as a locus of the contact lines between Σ_1 and Σ_2 in the fixed space:

$$\begin{aligned} x_p &= x_p(u, \vartheta), \\ y_p &= y_p(u, \vartheta), \\ z_p &= z_p(u, \vartheta), \\ n_{1,x_p} &= n_{1,x_p}(u, \vartheta), \\ n_{1,y_p} &= n_{1,y_p}(u, \vartheta), \\ n_{1,z_p} &= n_{1,z_p}(u, \vartheta), \\ [x \ y \ z \ t]^T &= M_{sp} [x_p \ y_p \ z_p \ t_p]^T, \\ [n_{1,x} \ n_{1,y} \ n_{1,z}]^T &= L_{sp} [n_{1,x_p} \ n_{1,y_p} \ n_{1,z_p}]^T, \\ n_{1,x} V_{12,x} + n_{1,y} V_{12,y} + n_{1,z} V_{12,z} &\equiv f_s(u, \vartheta, \varphi_1) = 0. \end{aligned} \quad (4)$$

Here M_{sp} and L_{sp} are correspondingly 4x4 and 3x3 transition matrices from S_p into S .

Analogically, the contact lines on Σ_1 can be written in the coordinate system $S_g(O_g, x_g, y_g, z_g)$ of the second movable link $i = 2$.

In general, the defined geometry, dimensions and placement of the mesh region in the fixed space, as a part of the action surface, are the optimal ones, if:

- singular points of second order (**undercutting points**) are registered and eliminated;
- singular points of first order (**ordinary nodes of contact**) are registered and eliminated;
- the orientation and placement of the contact lines on the mesh region is chosen, in order to achieve the maximum loading capacity and coefficient of efficiency.

In many cases the synthesis of spatial gear drives with crossed axes is appropriate to be realized by combination of the two main approaches for synthesis [2]. The general strategy of such approach is based on:

- to construct such models, which allow that the basic geometric-kinematic characteristics at the pitch contact point to be determined.
- establishment of system of criteria, which will control concrete set of characteristics, that define different quality features for the whole mesh region or at least for some limited and preliminary defined part of it.

The approach to the synthesis upon a mesh region is offered by the authors of this study, when the mathematical model and computer program for synthesis of some less studied, not only in Bulgaria, hyperboloid gear drives (gear mechanisms of type Wildhaber) (see Fig.4) [2, 6,-10] are organized.

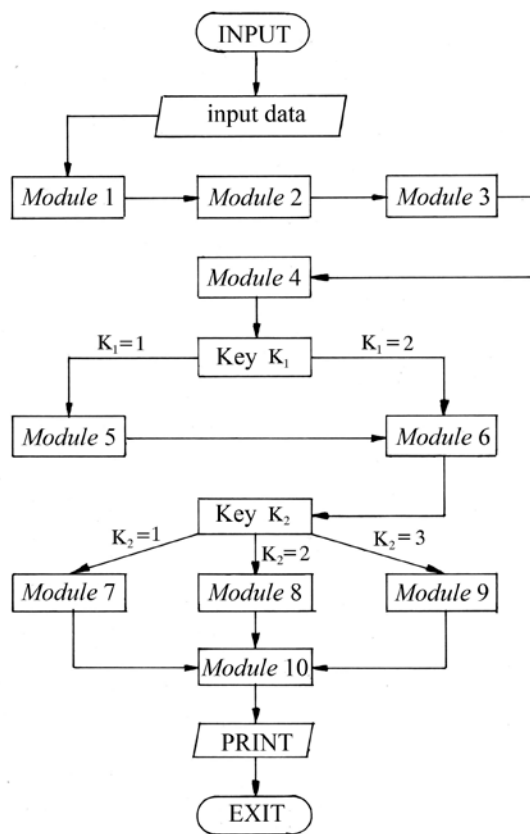


Fig. 4. General structure of the research program for synthesis of gear mechanisms of type Wildhaber

The structure of this program for the synthesis contains Modules and it is described as follows:

Module 1. In this first module, the offset a_w is directly chosen with a standard value or by the maximum torque $M_{2,max}$ of the driven link;

Module 2. It serves to realize an adequate choice of the number of the helical teeth (threads) Z_1 of the torus shaped worm of type Wildhaber gears;

Module 3. Here, the choice of the coefficient q of the reference diameter of the Wildhaber worm in the throat sector is realized;

Module 4. This module is oriented into determining the profile angle $\alpha^{(j)}$, ($j = 1, 2$) of the teeth of the cylindrical gear with the straight plane teeth;

Modules 5 and 6. They analyze the existence of the singular points of first and second order respectively;

Module 7. In this part of the program, the algorithm is oriented towards the optimization of the synthesized gear pair of type Wildhaber on the basis of its hydrodynamic characteristic;

Module 8. It ensures the evaluation of the contact strength of the studied gear mechanisms. This assessment is realized in the process of the synthesis and analysis;

Module 9. This module covers the optimization of the synthesized gear sets Wildhaber, in relation to their durability;

Module 10 serves to print the table, which consists the basic geometric parameters of the synthesized gear set of type Wildhaber.

3. Conclusion

The presented here study has evolved and improved over time. As a result of the created computer programs, dozens of gear mechanisms were synthesized [2, 6-10]: Spiroid, Helicon, Wildhaber and Planoid. Some of these spatial gear drives have been realized as industrial models, and many of gear sets of type Helicon have been manufactured and implemented into various engineering constructions. The theoretical and applied studies carried out are accompanied by an active innovation activity related to the creation of nine Bulgarian inventions registered in the Bulgarian Patent Office [2].

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QUALITY CONTROL METHODS FOR THE EVALUATION OF QUALITY STABILITY OF REINFORCING BARS

МЕТОДЫ КОНТРОЛЯ КАЧЕСТВА ПРИ ОЦЕНКЕ СТАБИЛЬНОСТИ ПРОИЗВОДСТВА АРМАТУРНОГО ПРОКАТА

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Abstract: The evaluation of the quality of production process on mechanical properties of reinforcing bars profile 10-32 of steel grade 35GS was performed, obtained in the conditions of the rolling production of JSC "ArcelorMittal Temirtau". Using a complex quality parameter, the process of rebar production is characterized as stable and controlled.

Keywords: reinforcing steel, periodic profile, chemical composition, mechanical properties, production process quality assessment.

1. Introduction

Statistical methods are used not only to develop new technologies for producing long products with a certain set of properties, but also to control the existing production technology. For example, monitoring of the stability of the technological process at PJSC "Dneprostal" [1] in accordance with the technological instructions was carried out by means of analytical tools of the software package of statistical data processing "Statistica" of Star Soft, described in work [2].

The authors of the work [1] conducted a passive quality assessment by collecting data of the produced serial material on the results of acceptance control of product quality parameters, namely: chemical composition, macro-and microstructure, characteristics of mechanical properties for compliance with the requirements of regulatory documentation. In the analysis of statistical data of chemical composition and standard mechanical properties, the authors determined such descriptive statistics, which give general information about the distribution of the investigated product quality parameter:

- minimum and maximum value of the estimated parameter;
- the average value of the estimated parameter ($\bar{X}$) or the average estimate calculated as the arithmetic mean of the observation (center of distribution);
- standard deviation (scattering) (σ) - a measure of the variability (variation) of the parameter, reflecting its spread relative arithmetic mean;
- coefficient of variation (V) showing the fluctuation of the individual values around the mean and expresses a measure of the variability of the parameter in percent.

2. Method of evaluation of the quality of production process

To evaluate the type and consistency of the parameters of the distribution based on the definition of species, in work [1] the stability of the mechanical properties in the process of production was tested. As a rule, the behavior of the measured characteristics obeyed the law of normal distribution, or distributions, slightly different from the normal. The test parameters were the arithmetic mean and standard deviation. The bell-shaped form of the normal distribution function has two inflection points. Distance from data points to the vertex equals the standard deviation (σ). The highest frequency of the level of mechanical properties accounted for the middle of the interval, to the ends of the frequency smoothly decreases. Typically, the curve is symmetric about the mean. The area under the normal distribution curve, or, in other words, the Gauss curve, is 1 or 100%, regardless of the standard deviation. The property of normal distribution is subject to the rule $\pm 3\sigma$ - standard deviations (three Sigma), it is possible to calculate the probability of getting the values of the variable in the specified maximum permissible borders (high and low) or to determine the

percentage of attacks that were beyond these tolerance limits. The area inside the three Sigma borders is called a statistical process, equal to 6σ .

The criterion for assessing the stability of product quality and suitability of the process in work [2] the total quality parameter $P_{q.p.}$ was chosen, which was defined as the ratio of the scope of the tolerance to the scope of the process, i.e. the statistical tolerance of the process.

The stability of the process was determined by the value of $P_{q.p.}$:

- at $P_{q.p.} < 0.67$ - the technological process of production was considered unstable and uncontrolled, and requires adjustment;
- at $0.67 \leq P_{q.p.} \leq 1.11$ - the production process was considered stable or controlled, but required adjustment through additional analysis;
- at $P_{q.p.} \geq 1.11$ - technological production process is considered stable, controllable and manageable.

The upper and lower limits of characteristics according to the regulatory documentation - the lower and upper maximum permissible limits were set as follows:

$$P_{q.p.} = \min(C_n^{LB}; C_n^{HB}),$$

where $C_n^{LB} = (\bar{X} - LB) / 3\sigma$ - lower indicator of the suitability of the technological process;

$C_n^{HB} = (HB - \bar{X}) / 3\sigma$ - higher indicator of the suitability of the technological process.

3. Results and discussion

To study the stability of the production process in shape rolling shop of JSC "ArcelorMittal Temirtau", the authors formed an array of experimental data of calibrated (reinforcing) rolled periodic profiles from 35GS steel grades with diameters from 10 to 32 mm. Experimental data were collected in the period July to August 2014 on continuous 16-cage mill 320. The volume of data contains 179 values.

As indicators characterizing the quality of rebar were selected: the chemical composition of the metal content of the main elements - carbon (C,%), manganese (Mn,%), silicon (Si,%), chromium (Cr,%), nickel (Ni,%), copper (Cu,%), aluminum (Al,%), the content of harmful impurities of nitrogen (N,%), sulfur (S,%) and phosphorus (P,%), as well as indicators of the most important mechanical properties - yield strength (σ_y , MPa), tensile strength (σ_T , MPa), elongation (δ ,%). Chemical composition and properties of the steel tested on the basis of Memorandum of cooperation together with the central laboratory of JSC "AMT" to meet the requirements of GOST 5781-82, GOST 10884-94.

The studied steel grades are widely used at JSC "ArcelorMittal Temirtau" for the production of rebar of periodic profile. For

statistical processing of data of rebar 179 periodic profiles were used. According to the method described in [4], statistical processing of sample data on the chemical composition and mechanical properties of hot-rolled reinforcement was carried out. Using the above method, we conducted an integral assessment of the stability of the technological production of rebar of all profiles.

The statistical analysis of mechanical properties of reinforcing steel of 35GS grades of profile numbers from 10 to 32 showed compliance of chemical composition with requirements of documentation. For reinforcing steel of 35GS grades, the results of compliance with the criteria for assessing the stability of the process were obtained (table 1).

Table 1 - Statistical characteristics of the mechanical properties of reinforcing bars profiles №10-32 from 35GS steel

Characteristic	Requirements	Xmin-Xmax/X	Scattering σ	Coefficient of variation	$P_{q.p.}$	
					For 3σ	For 6σ
Yield strength (σ_Y , MPa)	390	370-525/437,82	22,14	5,06	0,72	0,36
Tensile strength (σ_T , MPa)	590	550-830/669,80	38,68	5,77	0,69	0,34
Elongation (δ ,%)	14	13,6-31/22,14	3,03	13,71	0,89	0,45

The obtained data confirm the stability of the technological process of obtaining reinforcing steel of 35GS grade, fully meeting the requirements of GOST according to the obtained level of mechanical properties. For yield strength and tensile strength $P_{q.p.}$ is 0.72 and 0.69, respectively. 35GS steel with a sufficiently large margin of strength characteristics has a fairly stable plastic properties, which provided $P_{q.p.}$ a value greater than 0.7 in elongation ($\delta=0.89$), which is proof of the stability of the process, but requires further analysis and possible adjustment. Therefore, an attempt was made to divide the existing general set into 3-4 samples. For example, in accordance with the materials [5], it is advisable to divide the set into size groups by the values of the diameter of the rolled products. The work [5] is based on the fact that the profile №20 is transitional and can be attributed to both large and medium.

The division into three clusters (small, medium and large profiles) was performed as follows: Ø10-16mm, Ø18-22mm and Ø25-32mm. Since the small profiles in the general population are the absolute majority, so the group of small profiles was divided into 2 parts: Ø10-12mm and Ø14-16mm (table 2). Thus, finally we got 4 samples.

Table 2 – Samples, sorted by size profile

Profile group	10-12	14-16	18-22	25-32
Sample size	60	54	30	25

The samples were subjected to all statistical tests. The results of compliance with the criteria for assessing the stability of the process were given in tables 3-6.

Table 3 - Statistical characteristics of the mechanical properties of reinforcing bars profiles №10-12 from 35GS steel

Characteristic	Requirements	Xmin-Xmax/X	Scattering σ	Coefficient of variation	$P_{q.p.}$
Yield strength (σ_Y , MPa)	390	415-470/438,50	13,63	3,11	1,19
Tensile strength (σ_T , MPa)	590	550-735/662,75	34,28	5,17	0,71
Elongation (δ ,%)	14	18-31/24,12	2,98	12,36	1,13

Table 4 - Statistical characteristics of the mechanical properties of reinforcing bars profiles №14-16 from 35GS steel

Characteristic	Requirements	Xmin-Xmax/X	Scattering σ	Coefficient of variation	$P_{q.p.}$
Yield strength (σ_Y , MPa)	390	400-455/436,20	13,63	3,12	1,13
Tensile strength (σ_T , MPa)	590	615-720/670,74	24,85	3,70	1,08
Elongation (δ ,%)	14	13,6-25/21,31	2,15	10,08	1,13

Table 5 - Statistical characteristics of the mechanical properties of reinforcing bars profiles №18-22 from 35GS steel

Characteristic	Requirements	Xmin-Xmax/X	Scattering σ	Coefficient of variation	$P_{q.p.}$
Yield strength (σ_Y , MPa)	390	410-465/433,50	15,77	3,64	0,92
Tensile strength (σ_T , MPa)	590	640-720/667,83	24,24	3,63	1,07
Elongation (δ ,%)	14	18-27,5/22,42	2,33	10,38	1,21

Table 6 - Statistical characteristics of the mechanical properties of reinforcing bars profiles №25-32 from 35GS steel

Characteristic	Requirements	Xmin-Xmax/X	Scattering σ	Coefficient of variation	$P_{q.p.}$
Yield strength (σ_Y , MPa)	390	410-460/434,4	12,27	2,83	1,21
Tensile strength (σ_T , MPa)	590	630-730/674,6	21,89	3,24	1,29
Elongation (δ ,%)	14	17,5-24/20,46	1,62	7,92	1,33

Statistical processing of rebar profile № 10-12 mm of steel 35GS showed compliance with the main material quality indicators (tables 3-6

). The results of tests of mechanical properties of reinforcing steel 35GS profiles №10-12 mm showed that $P_{q.p.}$ was in the range of 0.71-1.19, which characterizes the production technology as

stable and controlled (table 4). The stability of the production process of rebar profile №14-16 is confirmed by the quality parameters, varying from 1.08 to 1.13, characterizing the

production process as stable and meets the requirements for supply. Evaluation of the production process in the preparation of rebar profile №18-22 carried out by the values of yield strength and 0.92 and 1.07, respectively, has a fairly stable plastic properties, providing $P_{q.p.} = 1.21$ in relative elongation and characterizes the production process as stable and controlled, satisfying the requirements. The stability of the production process of rebar profile №25-32 is confirmed by the quality parameters, varying from 1.21 to 1.33, characterizing the production process as stable and meets the requirements.

4. Conclusions

1. The results of statistical processing of the main quality indicators on the chemical composition of the smelting and mechanical properties of rebar profile numbers 10-32 of 35GS steel confirmed the compliance of the technological process in terms of grade production of JSC "ArcelorMittal Temirtau" to requirements for supply, production is stable.

2. To carry out additional analysis of the process and its possible adjustment, the existing general set was divided into four clusters according to the profile size criteria.

3. Assessment of production of reinforcing bars to clusters, at mill 320 JSC "ArcelorMittal Temirtau" has confirmed the stability of the technological process and meets the regulatory requirements for supply.

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NOVEL TECHNOLOGY OF METAL POWDERS PRODUCTION BY HYDRO-VACUUM DISPERSION OF MELTS

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Abstract: A novel technology for producing metal powders is presented, the distinctive feature of which are the conditions of forming of powder particles. In particular, under the proposed technology the melt is sucked bottom-up by the vacuum produced by the toroidal vortex of the discharged nucleus of high-pressure water flow in the two-layer cylindrical shell cavity, where it is being dispersed as metallic particles and carried over from the working medium to a special store. The so produced powders have a particular morphology and structure, increased specific surface area and microhardness.

KEYWORDS: METAL POWDERS, MELT, SPRAYING, DISPERSION, PULP

At present, dispersion of melts by the high-pressure water is the most popular technology for producing metal powders. The essence of this process consists in the fact that the falling down vertical flow of metal is dispersed by the cross-sectional high-pressure water flows [1-3]. At high dispersion speeds also great are the aerodynamic forces contributing to the formation of a significant part of oxides (formation of the primary oxide film occurs practically instantaneously). As a result of the dissociation of water vapors at high temperatures, the formation of oxygen is also possible in the spraying area. After the process of spraying and temperature reduction is over, the dissolved oxygen is extracted from metal, becoming the reason of porosity of the sprayed powders and articles therefrom. It is noteworthy that nitrogen also gets into the melt in all the technology stages. It dissolves well in iron and other metals with the production of nitrides, which leads to the increasing the hardness and reduction of the plasticity of powders. Therefore, the dispersion-produced powders are subjected to recovery annealing, the purpose of which is not only the recovery of oxides, but also the improvement of the such technological properties of the powders as compressibility, sintering ability, etc. [4-6]. The same takes place during the centrifugal, ultrasound and other methods of dispersion.

In contrast to the available technologies, the developed one provides for dispersion of melts by the technological operation of hydro-vacuum pumping [7]. The functional scheme of the technological process of hydro-vacuum dispersion of melts is

shown in Fig. 1. By supplying high-speed water flow in the closed system of special ducts, a discharge is generated in the area of the bottom edge joint if these ducts at the upper head projecting on the external face of the cylinder nozzle body, by the force of which suction of the melt toward the area of high-speed hydrodynamic volume effect is taking place. The proposed technological solution principally differs by its functionality, stability and low price, where the common high-pressure process water circulating by the closed path serves as an energy carrier. The principal functional feature of the hydro-vacuum suction device can be considered its ability to create a volume toroidal vortex with the discharged nucleus, at the expense of which the suction and primary fragmentation of the trapped and vertically movable (against the force of gravity) melt take place (see Fig. 2). Since the contact of melt drops with the air in the dispersion device is excluded. The process of oxidation of particles is also prevented. It should also be mentioned that the high-vacuum melt dispersion technology is ecologically safe, because no dust and gas emission to the environment takes place and the water itself does not require to be filtered from solid impurities, since the dispersion in our case is carried out without employment of special spray jets. All this offers additional advantages to the technology under consideration.

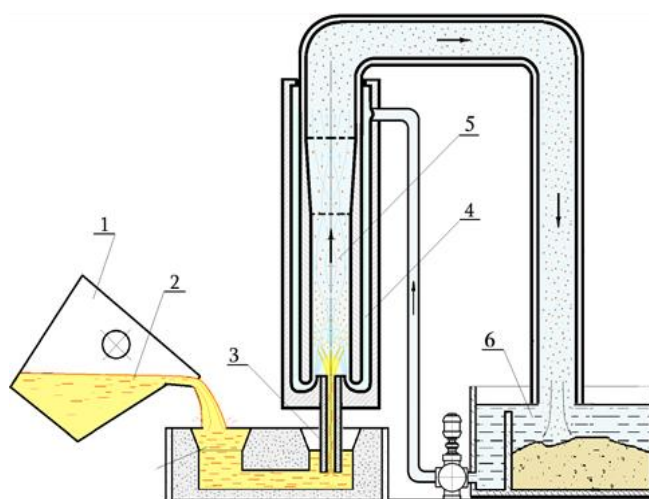


Fig. 1: Functional scheme of the process of hydro-vacuum dispersion of a melt

1-ladle; 2-melt; 3-suction head;
4-high-pressure water; 5-pulp;
6-powder store

Experimental studies, which were carried out at water pressure of 16 kg/cm², which, in turn, created in the bottom head of the cap vacuum - 0,8 kg/cm², demonstrated that the mechanism of practical implementation of the proposed method and of the device of hydro-

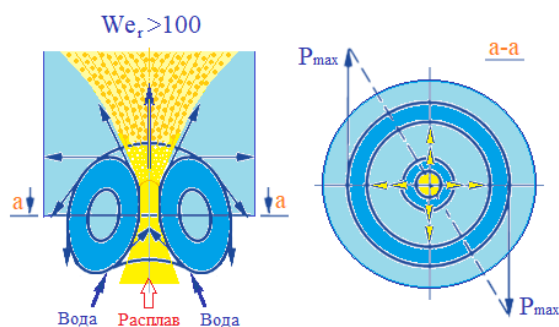


Fig. 2: Hydrodynamic structure of the produced toroidal vortex, where We_r is the rotary Weber number

vacuum suction of melts principally differs from the water dispersion mechanism. Upon hydro-vacuum suction, from the moment the melt jet gets into the inlet box of the end head, where it is surrounded by a circular high-pressure water flow, produced by

the mentioned toroidal vertex (Fig. 2). This force hydrodynamic effect forms the vertically directed cone flow with the angular acceleration, with the corresponding tangential and radial stresses, as a result of which the flow abruptly widens and is diminished by the flush (cavitation) mechanism of the layer-by-layer disruption of the cone flow. Under the values $We > Re^{0.5}$, the destruction will be of the explosive spattering nature (speed > 500 m/s).

On the surfaces of the crushed and supercooled metal water vapor bubbles are immediately formed, frequently producing a vapor film; while not being accumulated, they are removed from the working area occasionally with the formed dispersed particles. However, the bubbles/films, because of fast condensation of their

water vapor and abrupt fall of the internal pressure, quickly collapse (close up) and form hydraulic micro-shocks, which, in turn, conditions secondary destruction and deformation of case-hardened metal shards. In the end, the output generally consists of mechanically strengthened (mechanically activated), tempered powders of a complex flaky shape/form, with increased specific surface. Evidence of this are figures 3 and 4, demonstrating the surface morphology and micro-hardness of the particles produced by the proposed method. For clarity, Fig. 5 individually shows microfractographs of synthetic cast iron of different dominating fractions.

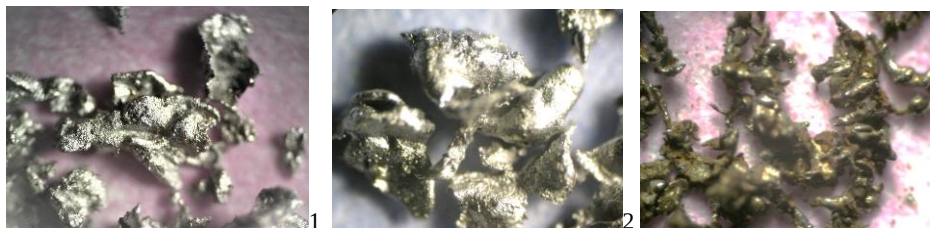


Fig. 3. Morphology of surface of the powders produced by the technology of hydro-vacuum dispersion of melts. 1) Al, 2) Mg 90-Al 10%, 3) CI-3.5% C, $\times 40$

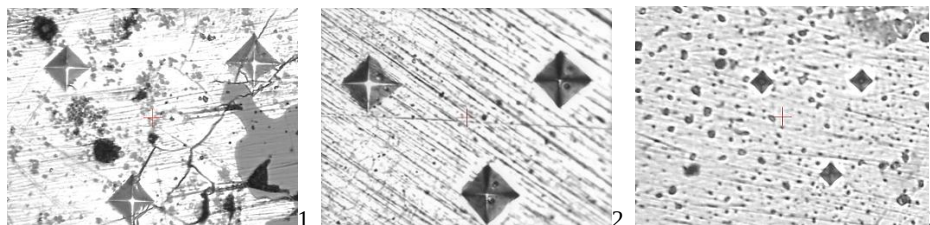


Fig. 4. Powder micro-hardness, load on indenter 200 mN.
1) Al - 164 HV, 2) alloy MgAl - 118 HV, 3) cast iron - 880 HV



Fig. 5. Microfractograph of the powders of gray cast iron 3.5% C of different fractions, μm ($\times 25$).
1) +800-1000; 2) +500-800; 3) +200-500

Experimental studies revealed that the crystallization of liquid metal drops (flakes) is carried out at significant overcooling of the melt and high speeds of cooling within: 10^3 - 10^4 °C/c. Metallic powder particles are represented by a highly refined cellular-dendritic microstructure. The size of cells and distances between secondary axes of dendrites constitute

1-5 μm , depending on the cell sizes. The carbide phase in the form of a thin net is located along the cell borders and interaxial sections of dendrites, the carbide phase representing a peculiar reinforcing, wear-resistant framework, retaining the shape and strength/solidity of powder particles (Fig. 6).

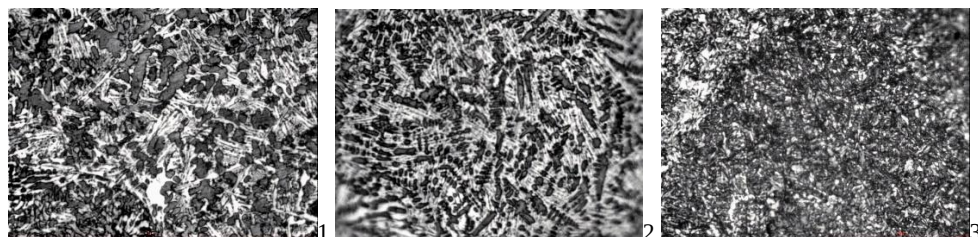


Fig. 6. Microstructure of hydrodynamically dispersed synthetic cast iron ($\times 1000$).
Dispersion, μm : 1) +800-1000; 2) +500-800; 3) +200-500

For a deeper investigation of the phase composition of powders an X-ray spectrum analysis of the phase composition was used (Fig. 7). It was found that iron, instead of the expected cementite and ferrite phases – the solid solution of carbide implantation in α -iron with volume-centered lattice, is represented by the phase of cementite and austenite – the solid solution of carbide implantation in γ -iron with the face-centered cubic lattice. For the purpose of a comparative analysis of the phase composition of the powder produced by us with the widely distributed *Hoganas* metal powder, Fig. 7 presents the X-ray spectrum analysis of this powder, where γ -iron is completely absent and the phase is represented exclusively by α -iron, which can be explained by the significantly different conditions of hardening and temperature of

cooling being formed during dispersion of the particles of our powder. It should be noted in favor of the proposed method that the produced powder does not require the restoration of oxides and is subjected to drying only at 130 °C, fully preserving the unbalanced structure with γ -iron. Accordingly, it is chemically more active than the *Hoganas* powder, fire-reduced and with α -iron. In Fig. 7, the blue (lower) contour describes the phase composition of our powder before drying, while the red (upper) contour describes the phase composition after drying. Both are identical. This factor can be distinguished as one of the most important distinctive features and obvious productive advantages as compared with the existing methods of dispersion of metal melts.

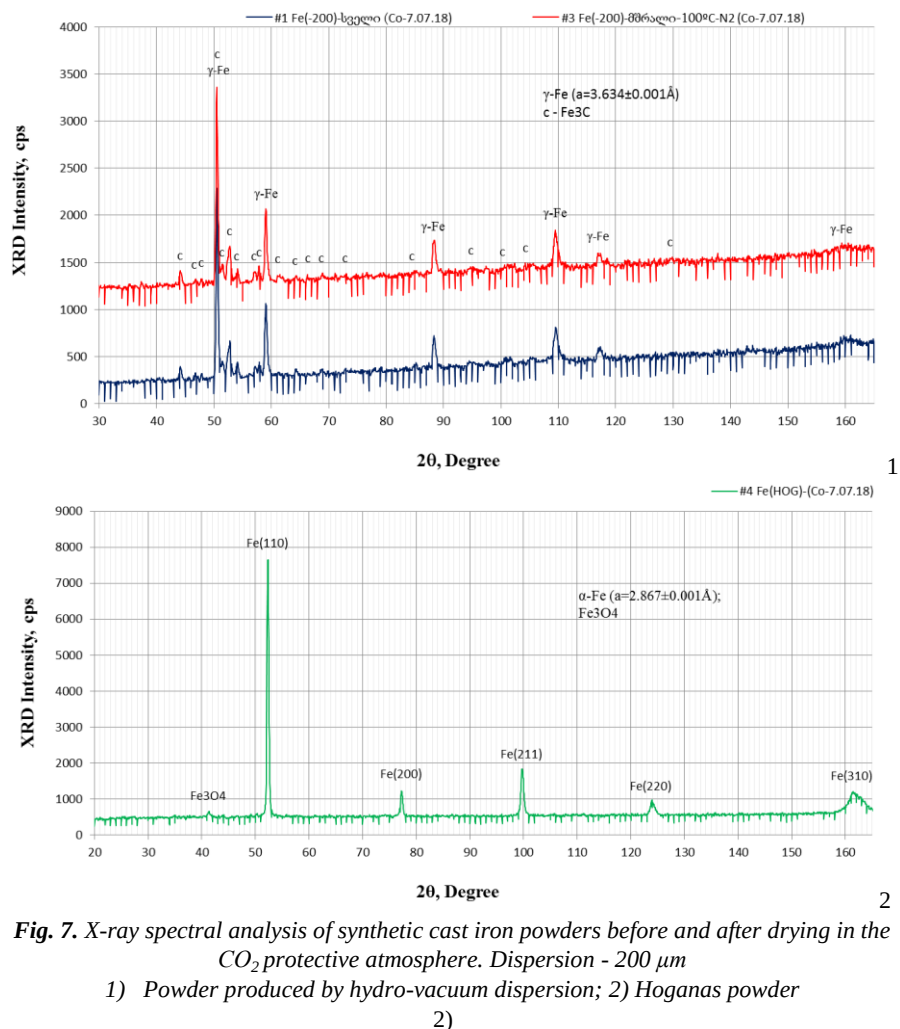


Fig. 7. X-ray spectral analysis of synthetic cast iron powders before and after drying in the CO_2 protective atmosphere. Dispersion - 200 μm
1) Powder produced by hydro-vacuum dispersion; 2) Hoganas powder

Experiments demonstrated that the melt's superheat value, suction rate, pressure and water temperature generated by the hydro-vacuum suction determine dispersion of the produced powder. The maximum production of the process during dispersion of aluminum makes 120 kg/min, and 425 kg/min – in the case of cast iron. The exclusion of the need to restore oxides makes the technology highly profitable. Since no

vapor, dust and gases are emitted into the air, the technology can be regarded as environmentally friendly. In its turn, the production tools are distinguished by their compactness, ergonomic characteristics, low noise level, as well as a possibility of controlling the technological parameters and the process. The structural process control model is illustrated as a process chart in Fig. 8.

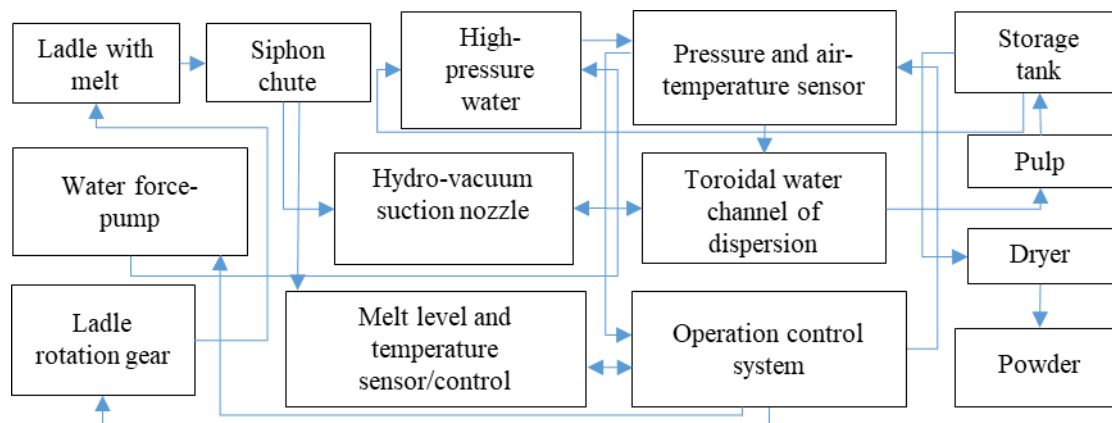


Fig. 8. Process chart of production of disperse metal materials by hydro-vacuum dispersion of melts

The melt flows from the ladle to a special siphon chute, where it is purified from non-metallic impurities and goes as a laminar flow to the hydro-vacuum suction nozzle. From the nozzle, by force of the in-channel vacuum generated by the toroidal vertex of high-speed water flow, the melt is sucked-off within the dispersion area, where it is subjected to the hydrodynamic volume action, decomposition/break-up and mixing with water, by the flow of which is then delivered as a pulp to the storage tank. After deposition and drying in the protective atmosphere (without reducing firing), the powder of the intended fractions ready for purposeful use is produced. The fractional composition can be regulated by controlling the melt suction temperature and rate, as well as the circulating water pressure and temperature, for which purpose the system is provided with controls/sensors of the melt level and temperature in the siphon chute and of the pressure and water temperature in the water channel of dispersion. Electronic signals from the sensors are integrated in the operations control system, where the current indications/data are compared with the reference data. In case of necessity, a respective control signal is developed and communicated to the actuators. The rotation gear drive of the pouring ladle and the electric motor serve as the actuators. Thus, an on-line correction of the production cycles and quality control of the produced powder is carried out.

A systems analysis of the foregoing functional peculiarities and results of experimental studies of the technology of hydro-vacuum dispersion of melts shows that the following technical advantages can be cited for substantiating high performance of the proposed technology:

1. The possibility of exclusion of a contact of particles with the atmosphere in the course of the powder forming and cooling;
2. The condition of particles' forming in the force field directed against the gravitational force;
3. Formation of particles with an increased specific surface.

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PECULIARITIES OF STRESS-STRAIN STATE OF TOROIDAL PRESSURE HULL, MADE BY WINDING

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Abstract: The peculiarities of evaluation of stress-strain state of the pressure hull of the underwater technical device, shaped as torus with circle intersection, which was obtained by transverse winding combined with longitudinal winding (or facing) of polymer materials, while taking variable thickness by meridian section into an account, are presented.

Keywords: toroidal pressure hull, variable casing thickness, stress-strain state, winding, orthotropic casing.

1. Introduction

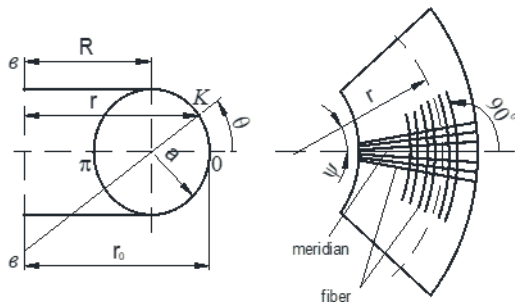
The method of winding with fiber is the main method of production of pressure hulls of underwater technical devices from polymer composite materials (PCM). A pressure hull of almost any size and with maximal values of physical and mechanical properties of fibrous PCM can be manufactured from PCM using this method. Creation of pressure hulls from PCM is easier from technological point of view, than the creation of similar constructions from metal.

During the design of minimal weight pressure hulls, evaluation of strength has one of the most significant places in the total volume of evaluations. Studies of stress-strain state (SSS) of thin casings is one of the important problems of ship mechanics.

The goal of work is the study of the peculiarities of evaluation of stress-strain state of toroidal pressure hulls, made from polymer composite materials.

2. Objective and research methodologies

Torus is one of the prospective shapes for pressure hulls of underwater technical devices. Such a complex shape of PCM-made pressure hull can be produced by using winding method. Method of transverse winding combined with longitudinal winding (or facing) is one of the variations of continuous winding method (see Fig. 1).



a – inner radius of meridian transection; R – the distance from rotation axis to the center of meridian transection; r_0 – maximal rotation radius (on the outer equator); r – the distance between rotation axis b - b and given point $K(\theta)$ of middle surface in meridian transection

Fig. 1. Geometric sizes and schemes of round toroidal casing made by transverse winding combined with longitudinal winding (or facing)

When toroidal casing is made by transverse winding combined with longitudinal winding (or facing) every transverse monolayer (total quantity of transvers layers is l_2) will have a variable thickness due to a more dense packing on the inner equator of casing (see Fig.1) [1]:

$$h_2(\theta) = h_1 \frac{1+k}{1+k \cos \theta}, \quad (1)$$

where $h_1 = h_{long} = \text{const}$ – the thickness of longitudinal monolayer in the batch (total quantity of longitudinal layers is l_1), which is equal to the thickness of reinforcing fiber (tape).

Orthogonally-armed composite material is formed as a result of such kind of winding. Thereafter, such toroidal pressure hull can be viewed as multilayer orthotropic casing, and the evaluation of elastic characteristics of material of the wall of wound toroidal casing can be performed by reduction of their real structure to multilayer model [2].

However, the concept of creation of toroidal casing as a pressure hull for underwater technical devices by winding method have not been created yet. The issues of optimal values of structural and technological parameters of wound toroidal pressure hulls from the strength point of view are still open.

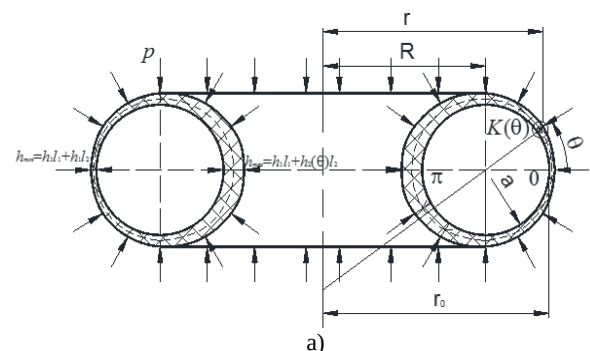
Casings, produced by winding, are the most complex for evaluation. Complexity lies in the inhomogeneity of elastic properties both by the thickness and in the direction of reinforcing layers, and in many existing methods of evaluation of plates and casings this fact is ignored. No evaluation of effective elastic modulus for such constructions was obtained yet, so they are evaluated as multilayer casings, reinforcing layers of which are considered as hard with given elastic properties that are found experimentally or theoretically. Winding brings technological restrictions to reinforcement scheme, namely the introduction of reinforcing material in the radius direction or under some degree to it makes the scheme sufficiently complex, and in many cases this scheme can not be described analytically.

3. Results and discussion

SSS of pressure hull with round transverse intersection, made by transverse winding combined with longitudinal winding (or facing) from carbon fiber reinforced plastic (CRP) and glass reinforced plastic (GRP) is studied in present paper.

Solution of this task is given in discrete setting, when quantities of layers in each direction of their reinforcement are used as project parameters. This allows taking technological peculiarities of the structure of toroidal pressure hull, obtained by continuous winding method, into account during the optimization.

The orthotropic toroidal casing, made from PCM, is considered as a pressure hull of underwater technical device (see Fig. 2).



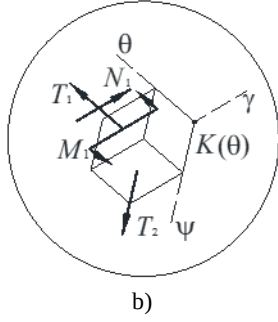


Fig.2. Geometric parameters of diametric intersection of variable thickness toroidal casing (a) and stressed state in the point of $K(\theta)$ type of middle surface of the casing (b)

Stress-strain state of closed variable thickness toroidal casing under the impact of evenly-distributed outer pressure p [Pa] is considered as an axial-symmetric task (by ψ coordinate). The system of equations of equilibrium for an axial-symmetric task (see Fig. 2, b) for orthotropic toroidal casing for point $K(\theta)$ is as follows [3]:

$$\begin{cases} \frac{\partial BT_1}{\partial \theta} - \frac{\partial B}{\partial \theta} + ABk_1N_1 = 0 \\ -(k_1T_1 + k_2T_2) + \frac{1}{AB} \frac{\partial BN_1}{\partial \theta} = p \end{cases}, \quad (2)$$

where $A = a$ i $B = \frac{a}{k}(1 + k\cos\theta)$ – Lamé coefficients for toroidal surface; $k = \frac{a}{R}$ – geometric parameter of torus shape; k_1, k_2 – main curvatures; N_1, T_1, T_2 – linear stresses.

In the formula (2) and all the subsequent formulas the 1 and 2 indexes correspond to two curvilinear coordinates θ and ψ respectively.

The hypothesis of straight normals, according to which the points that lie on the normal to middle surface before a deformation, remain lying on the straight line that is normal to middle surface after a deformation, is taken as a basis of thin casings bending theory. In other words, the straightness of normal is slightly violated during the deformation process. This is due to the shears in intersections, that are normal to middle surface. This the hypothesis of straight normals boils down to the assumption that the shears in normal intersections are relatively small if compared to the degrees of the normals turns, and thus the shear deformation can be disregarded in most cases [4].

Geometric relations are as follows:

$$\begin{aligned} \varepsilon_1 &= \frac{1}{A} \frac{\partial u(\theta)}{\partial \theta} + k_1 w(\theta), \\ \varepsilon_2 &= \frac{1}{AB} \frac{\partial B}{\partial \theta} u(\theta) + k_2 w(\theta), \\ \chi_1 &= -\frac{1}{A} \frac{\partial}{\partial \theta} \left(\frac{1}{A} \frac{\partial w(\theta)}{\partial \theta} \right) + \frac{\partial k_1}{\partial \theta} \frac{u(\theta)}{A}, \\ \chi_2 &= -\frac{1}{A^2 B} \frac{\partial B}{\partial \theta} \frac{\partial w(\theta)}{\partial \theta} + \frac{\partial k_2}{\partial \theta} \frac{u(\theta)}{A}. \end{aligned} \quad (3)$$

where $u(\theta)$ – tangential displacement of $K(\theta)$ point by the angular coordinate θ ; $w(\theta)$ – radial displacement of $K(\theta)$ point by the radius of torus meridian intersection.

Evaluations of linear stresses and moments in $K(\theta)$ point are as follows:

$$\begin{aligned} N_1 &= \frac{1}{AB} \frac{\partial BM_1}{\partial \theta}, & N_2 &= 0, \\ T_1 &= C_{11}\varepsilon_1 + C_{12}\varepsilon_2, & T_2 &= C_{22}\varepsilon_2 + C_{12}\varepsilon_1, \end{aligned} \quad (4)$$

$$M_1 = D_{11}\chi_1 + D_{12}\chi_2, \quad M_2 = 0.$$

Where C_{ij}, D_{ij} – roughness's of composite casing ($i, j=1, 2$). Roughness's C_{ij}, D_{ij} can be evaluated as [5]:

$$\begin{cases} D_{11}(\theta) = R_1 h_2^2(\theta) + R_2 h_2(\theta) + R_3 h_2^3(\theta) + R_4 \\ D_{22}(\theta) = R_5 h_2^2(\theta) + R_6 h_2(\theta) + R_7 h_2^3(\theta) + R_8 \\ D_{12}(\theta) = R_9 h_2^3(\theta) + R_{10} h_2^2(\theta) + R_{11} h_2(\theta) + R_{12}, \\ C_{11}(\theta) = R_{13} + R_{14} h_2(\theta) \\ C_{22}(\theta) = R_{15} + R_{16} h_2(\theta) \\ C_{12}(\theta) = R_{17} + R_{18} h_2(\theta) \end{cases}, \quad (5)$$

where Rf ($f = 1, 2 \dots 18$) is a function that depends on the parameters that describe the structure of winded toroidal casing and the properties of monolayer (reinforcing tape):

$$\begin{aligned} R_1 &= \frac{1}{12} h_1 l_1 [B_{11}(l_1^2 + 3l_2^2) + 2l_1 B_{22}(l_1 + 3l_2) + 2(B_{11} - B_{22})(3l_2 + 1)], \\ R_2 &= \frac{1}{12} h_1^2 l_1 [2B_{11}l_1^2 + B_{22}l_1^2 + 3l_2 l_1 B_{22} + 2(B_{22} - B_{11})], \\ R_3 &= \frac{1}{12} B_{22}(l_2 + l_1)^3, & R_4 &= \frac{1}{12} B_{11} h_1^3 l_1^3, \\ R_5 &= \frac{1}{12} h_1 l_1 [l_1^2 (2B_{11} + B_{22}) + 3l_2 (2l_1 B_{11} + l_2 B_{22}) + 2(B_{22} - B_{11})(3l_2 + 1)], \\ R_6 &= \frac{1}{12} h_1^2 l_1 [l_1^2 (B_{11} + 2B_{22}) + 3l_2 l_1 B_{11} + 2(B_{11} - B_{22})], \\ R_7 &= \frac{1}{12} B_{11}(l_2 + l_1)^3, & R_8 &= \frac{1}{12} B_{22} h_1^3 l_1^3, \\ R_9 &= \frac{1}{12} B_{21}(l_2 + l_1)^3, & R_{10} &= \frac{3}{12} B_{12}(l_2 + l_1)^2 l_1 h_1, \\ R_{11} &= \frac{3}{12} B_{12}(l_2 + l_1)^2 l_1^2 h_2, & R_{12} &= \frac{1}{12} B_{21} h_1^3 l_1^3, \\ R_{13} &= B_{11} h_1 l_1, & R_{14} &= B_{22}(l_1 + l_2), \\ R_{15} &= B_{22} h_1 l_1, & R_{16} &= B_{11}(l_1 + l_2), \\ R_{17} &= B_{12} h_1 l_1, & R_{18} &= B_{12}(l_1 + l_2). \end{aligned} \quad (6)$$

$$B_{11} = \frac{E_1}{1 - \mu_{12}\mu_{21}}, \quad B_{22} = \frac{E_2}{1 - \mu_{12}\mu_{21}}, \quad (7)$$

$$B_{12} = \frac{E_2 \mu_{12}}{1 - \mu_{12}\mu_{21}} = \frac{E_1 \mu_{21}}{1 - \mu_{12}\mu_{21}}.$$

$$E_1 = E_B \eta + (1 - \eta) E_M, \quad E_2 = \frac{E_B E_M}{\eta E_M + (1 - \eta) E_B}. \quad (8)$$

$$\mu_{12} = \mu_B \eta + (1 - \eta) \mu_M, \quad \mu_{21} = \frac{\mu_{12} E_2}{E_1}. \quad (9)$$

where η – coefficient of volume filling.

Elastic characteristic of monolayer (E_1, E_2, μ_{12} and μ_{21}) can be found experimentally or be calculated according to (8) and (9) mathematic models.

By inserting the values of deformation components from (3) into (4), and subsequent inserting of obtained evaluations for outer stresses and moments, as well as evaluations (1) and (5) into (2) and taking into account the fact that $C_{ij}(\theta)$ and $D_{ij}(\theta)$ roughness's are the functions of θ for the evaluation of variable thickness casing, the following evaluation of equilibrium in the displacements of closed variable thickness orthotropic toroidal casing can be obtained:

$$\begin{aligned} L_{11}(C_{ij}C'_{ij}D_{ij}D'_{ij})u + L_{12}(C_{ij}C'_{ij}D_{ij}D'_{ij})w &= 0, \\ L_{21}(C_{ij}C'_{ij}D_{ij}D'_{ij})u + L_{22}(C_{ij}C'_{ij}D_{ij}D'_{ij})w &= p, \end{aligned} \quad (10)$$

where linear differential operators L_{ij} are as follows:

$$\begin{aligned} L_{11}(C_{ij}C'_{ij}D_{ij}D'_{ij}) &= -C_{12}\cos\theta - D_{12}\frac{k+\cos\theta}{a^2(1+k\cos\theta)^2} - C_{22}\frac{k\sin^2\theta}{1+k\cos\theta} - C'_{12}\sin\theta - \\ &- D'_{12}\frac{\sin\theta}{a^2(1+k\cos\theta)} - C_{11}\sin\theta\frac{\partial}{\partial\theta} - D_{12}\frac{\sin\theta}{a^2(1+k\cos\theta)}\frac{\partial}{\partial\theta} + C'_{11}\left(\frac{1}{k}+\cos\theta\right)\frac{\partial}{\partial\theta} + \\ &+ C_{11}\left(\frac{1}{k}+\cos\theta\right)\frac{\partial^2}{\partial\theta^2} \end{aligned}$$

$$\begin{aligned} L_{12}(C_{ij}C'_{ij}D_{ij}D'_{ij}) &= -C_{11}\sin\theta + C_{22}\frac{k\cos\theta\sin\theta}{1+k\cos\theta} + C'_{11}\left(\frac{1}{k}+\cos\theta\right) + C'_{12}\cos\theta + \\ &+ C_{11}\left(\frac{1}{k}+\cos\theta\right)\frac{\partial}{\partial\theta} + C_{12}\cos\theta\frac{\partial}{\partial\theta} + D'_{12}\frac{1}{a^2}(\cos\theta+\sin\theta)\frac{\partial}{\partial\theta} + \frac{\sin\theta}{a^2}(D_{11}+ \\ &+ D_{12})\frac{\partial^2}{\partial\theta^2} - D'_{11}\frac{1}{a^2}\left(\frac{1}{k}+\cos\theta\right)\frac{\partial^2}{\partial\theta^2} - D_{11}\frac{1}{a^2}\left(\frac{1}{k}+\cos\theta\right)\frac{\partial^3}{\partial\theta^3} \end{aligned}$$

$$\begin{aligned} L_{21}(C_{ij}C'_{ij}D_{ij}D'_{ij}) &= C_{12}\frac{a^2k\sin\theta}{a^4(1+k\cos\theta)^3}\left(\frac{1}{1+k\cos\theta}+3k\cos\theta+\right. \\ &+ \left.\frac{k\cos^3\theta}{1+k\cos\theta}\right) + D_{12}\frac{k\sin\theta}{a^4(1+k\cos\theta)^3}\left(\frac{1}{1+k\cos\theta}-2k\right) + C_{22}\frac{a^2k^2\sin 2\theta}{a^4(1+k\cos\theta)^3}\times \\ &\times \left(\frac{1}{2(1+k\cos\theta)}+\cos\theta\right) - D'_{12}\frac{2k}{a^4(1+k\cos\theta)^3}(k+\cos\theta) - C_{12}\frac{a^2k\cos\theta}{a^4(1+k\cos\theta)^3}\times \\ &\times (3k\cos\theta+\frac{1+k^3\cos\theta}{1+k\cos\theta})\frac{\partial}{\partial\theta} - D'_{12}\frac{k\sin\theta}{a^4(1+k\cos\theta)^4}(1+2k\cos\theta+k^2\cos^2\theta)- \\ &- C_{11}\frac{1}{a^2(1+k\cos\theta)^4}(1+4k\cos\theta+6k^2\cos^2\theta+4k^3\cos^3\theta+k^4\cos^4\theta)\frac{\partial}{\partial\theta}- \\ &- D_{12}\frac{2k}{a^4(1+k\cos\theta)^4}(k+\cos\theta+k^2\cos^2\theta+k\cos^3\theta)\frac{\partial}{\partial\theta} - D'_{12}\frac{2k\sin\theta}{a^4(1+k\cos\theta)^4}\times \\ &\times (1+4k\cos\theta+2k^2\cos^2\theta)\frac{\partial}{\partial\theta} - D_{12}\frac{k\sin\theta}{a^4(1+k\cos\theta)^4}(1+2k\cos\theta+k^2\cos^2\theta)\frac{\partial^2}{\partial\theta^2} \end{aligned}$$

$$\begin{aligned} L_{22}(C_{ij}C'_{ij}D_{ij}D'_{ij}) &= -C_{11}\frac{1}{a^2(1+k\cos\theta)^2}(1+2k\cos\theta+k^2\cos^2\theta) - C_{12}\frac{2k\cos\theta}{a^2(1+k\cos\theta)} - \\ &- C_{22}\frac{k^2\cos^2\theta}{a^2(1+k\cos\theta)^2} + D'_{12}\frac{2k\cos\theta}{a^4(1+k\cos\theta)}\frac{\partial}{\partial\theta} + \frac{k\sin\theta}{a^4(1+k\cos\theta)}(D'_{12}-D_{12})\frac{\partial}{\partial\theta} + \\ &+ \frac{k\cos\theta}{a^4(1+k\cos\theta)}(D_{11}+2D_{12})\frac{\partial^2}{\partial\theta^2} + (D_{11}+D'_{12})\frac{k}{a^4(1+k\cos\theta)^2}(2\sin\theta+k\sin 2\theta)\frac{\partial^2}{\partial\theta^2} - \\ &- D'_{11}\frac{1}{a^4(1+k\cos\theta)^2}(1+2k\cos\theta+k^2\cos^2\theta)\frac{\partial^2}{\partial\theta^2} + D_{11}\frac{k}{a^4(1+k\cos\theta)^2}(2\sin\theta+ \\ &+ k\sin 2\theta)\frac{\partial^3}{\partial\theta^3} + D_{12}\frac{k\sin\theta}{a^4(1+k\cos\theta)}\frac{\partial^3}{\partial\theta^3} - D'_{11}\frac{2}{a^4(1+k\cos\theta)^2}(1+4k\cos\theta+ \\ &+ k^2\cos^2\theta)\frac{\partial^3}{\partial\theta^3} - D_{11}\frac{1}{a^4(1+k\cos\theta)^2}(1+2k\cos\theta+k^2\cos^2\theta)\frac{\partial^4}{\partial\theta^4} \end{aligned} \quad (11)$$

For the toroidal casing that is closed in both directions, the solution must be periodical to θ angle, thus in must be as follows:

$$\begin{aligned} u(\theta) &= \sum_{m=1}^{\infty} u_m \sin(m\theta), \\ w(\theta) &= \sum_{m=1}^{\infty} w_m \cos(m\theta). \end{aligned} \quad (12)$$

In order to achieve the necessary precision, finding three members of this row is enough to find the unknown values of u_m and w_m coefficients.

During the integration of equilibrium equation (10) using Bubnov-Galyorkin method [6] by θ and ψ by the surface of torus, it must be taken into the account that an element of torus area is equal to:

$$ABd\theta d\psi = \left[\frac{a^2(1+k\cos\theta)}{k} \right] d\theta d\psi, \quad (13)$$

The system of infinite linear algebraic equations is obtained after the transformations:

$$\begin{aligned} \sum_{m=0}^M (L_{11m}u_m + L_{21m}w_m) &= 0, \\ \sum_{m=0}^M (L_{21m}u_m + L_{22m}w_m) &= p. \end{aligned} \quad (14)$$

Solution of the system (5) at given $M=0,1,2,\dots,\infty$, gives values of u_m and w_m coefficients. Their substitution to (14) gives values of u and w movements for points of $K(\theta)$ type (see Fig.2).

Orthotropic toroidal casings (see Fig. 1), made from GRP and CRP, were considered as an example of pressure hull ($a = 1$ m, $k = 1/3$) of underwater technical device. Elastic characteristics of monolayer and averaged thickness of the batch were selected from the durability point of view according to the decision, considered in [7], for submersion depth of $H = 1000$ m ($P_{kr} = 10$ MPa): for casings made of GRP (S-2 GLAAS/Epoxy) – $E_1 = 59$ GPa, $E_2 = 20$ GPa, $\mu_1 = 0.28$, $h_{\Sigma}^{GRP} = 0.064$ m and for casings made of CRP (M35J/Epoxy) – $E_1 = 207$ GPa, $E_2 = 7.4$ GPa, $\mu_1 = 0.348$, $h_{\Sigma}^{CRP} = 0.04$ m. Monolayer thickness for casings made of GRP was $h_1^{GRP} = 0.25 \cdot 10^{-3}$ m, and for casings made of CRP it was $h_1^{CRP} = 0.2 \cdot 10^{-3}$ m.

Convergence of solutions (see Fig. 3) was analyzed on numeric examples for flexures w_m while holding value of end number of members of $M = 0,1,\dots,5$ row by m .

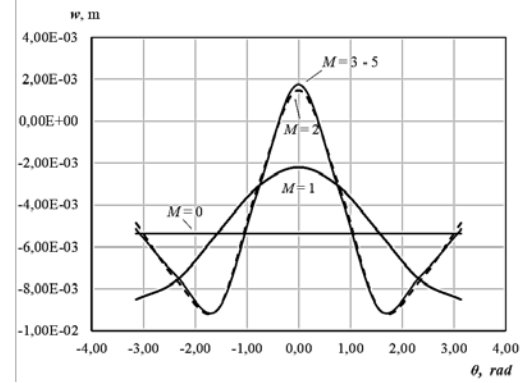
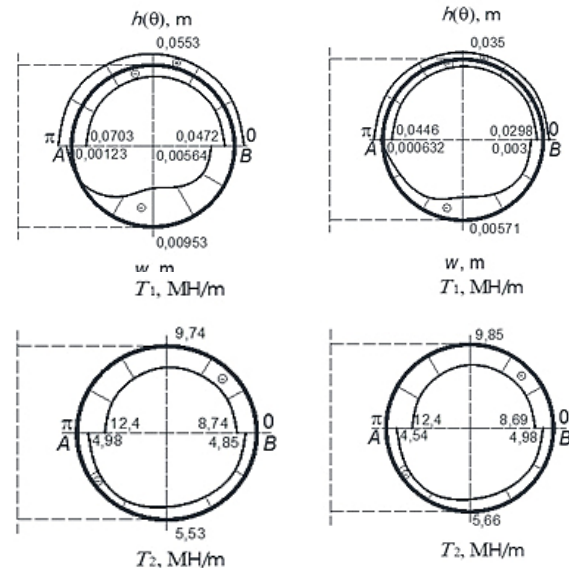


Fig. 3 Convergence of solutions for flexures of orthotropic toroidal casing under hydrostatic compression

Analysis of convergence of obtained solutions for flexures $w(\theta)$ of variable thickness orthotropic toroidal casing shows that holding of $M = 3$ row members is enough. It also should be noted, that maximal flexure is obtained at $\theta = \pm\pi/2$.

Diagrams of distributions of thicknesses, displacements and normal stresses for middle line on the meridian intersection of torus were built basing on solutions, obtained for u_m and w_m displacements. Diagrams of distributions of thicknesses $h(\theta)$, flexures $w(\theta)$, normal stresses $T_1(\theta)$ and $T_2(\theta)$, bending moment $M_1(\theta)$ and cutting force $N_1(\theta)$ in meridian intersection of torus at $M = 5$ are given at Fig. 4 for both considered casing materials.



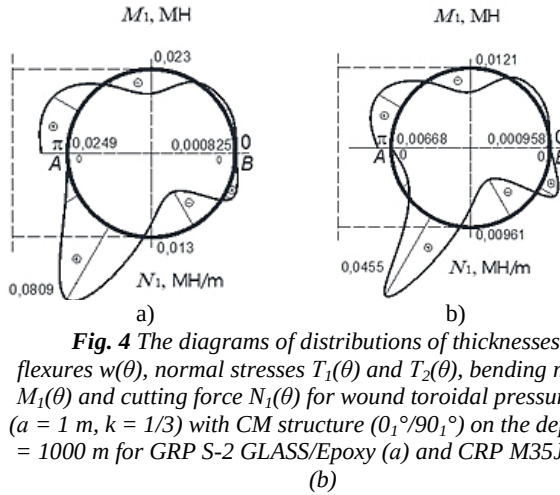


Fig. 4 The diagrams of distributions of thicknesses $h(\theta)$, flexures $w(\theta)$, normal stresses $T_1(\theta)$ and $T_2(\theta)$, bending moment $M_1(\theta)$ and cutting force $N_1(\theta)$ for wound toroidal pressure hulls ($a = 1$ m, $k = 1/3$) with CM structure ($0_1^\circ/90_1^\circ$) on the depth of $H = 1000$ m for GRP S-2 GLASS/Epoxy (a) and CRP M35J/Epoxy (b)

Diagrams of thicknesses $h(\theta)$ distribution shows the inhomogeneity of casing thickness due to the thickening of fibers on the inner pole A ($h_{\max} = 70.3$ mm $h_{\min} = 47.2$ mm for GRP and $h_{\max} = 44.6$ mm, $h_{\min} = 29.8$ mm for CRP) if compared to the inner pole B. The degree of casing thickness inhomogeneity can be described by the following relations $-h_{\max}/h_{\min} = 70.3/47.2 = 1.49$ for GRP and $h_{\max}/h_{\min} = 44.6/29.8 = 1.5$ for CRP. Averaged casing thicknesses, considered in the example [7], equivalent by the volume, were $h_{\Sigma}^{GRP} = 0.064$ m and $h_{\Sigma}^{CRP} = 0.04$ m. This could not help but affect the inhomogeneity of all other diagrams.

The diagram of flexures distribution $w(\theta)$ is very inhomogeneous. Maximal value of flexures is observed at $\theta = \pm\pi/2$ and equals to $w_{\Sigma}^{GRP} = 9.53$ mm and $w_{\Sigma}^{CRP} = 5.71$ mm. Their relations to the thicknesses of the casing is:

$$\frac{w_{\Sigma}^{GRP}}{h(\theta = \pm\pi/2)} = 0.172, \quad (15)$$

$$\frac{w_{\Sigma}^{CRP}}{h(\theta = \pm\pi/2)} = 0.163,$$

which allows considering the casing as thin even at $k = 1/3$. At $k < 1/3$ the casing is more homogeneous.

The diagram of normal stresses $T_1(\theta)$ is substantially inhomogeneous:

$$\frac{T_{1\max}^{GRP}}{T_{1\min}^{GRP}} = 1.42, \quad (16)$$

$$\frac{T_{1\max}^{CRP}}{T_{1\min}^{CRP}} = 1.43,$$

which is mainly due to $h(\theta)$ function, and maximum of normal stresses is observed at the pole A. Yet, the diagram of $T_2(\theta)$ distribution is almost homogeneous by the intersection.

The diagram of $M_1(\theta)$ distribution has two clearly expressed maximums at $\theta = \pm\pi/2$ and $\theta = \pm\pi/6$. The value of the moment at the pole B is insignificant.

The diagrams of cutting forces $N_1(\theta)$ have three maximums for GRP and four maximums for CRP, while their maximal values are insignificant. Maximal total values of σ_θ and σ_ψ stresses (see Fig. 5) for toroidal pressure hulls in both cases, that take the change of the thickness in transverse direction into account, are reached on the outer equator in the point B ($\theta = 0^\circ$).

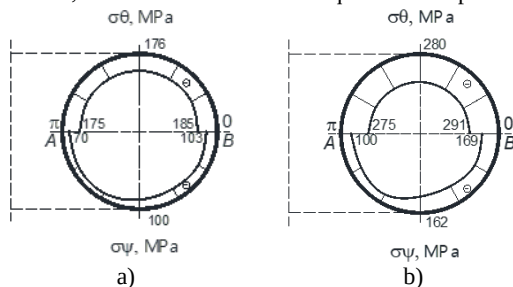


Fig. 5. The diagrams of distributions of σ_θ and σ_ψ stresses for wound toroidal hulls ($a = 1$ m, $k = 1/3$) with CM structure ($0_1^\circ/90_1^\circ$) at the depth of $H = 1000$ m for GRP S-2 GLASS/Epoxy (a) and CRP M35J/Epoxy (b)

It is shown, that taking the change of thickness during winding of transverse layers into account causes a significant impact on evaluated values of stresses. The main impact on SSS at point B is caused by $T_1(\theta)$ and $T_2(\theta)$ normal stresses.

At $P_{kr} = 10$ MPa maximal stresses at point B ($\theta = 0^\circ$) for GRP S-2 GLASS/Epoxy while taking variable casing thickness into account were $\sigma_\theta^{\max} = 185$ MPa and $\sigma_\psi^{\max} = 103$ MPa, and for CRP M35J/Epoxy they were $\sigma_\theta^{\max} = 291$ MPa and $\sigma_\psi^{\max} = 169$ MPa, while according to evaluation with an averaged thickness, like it was performed in work [7] according to Föppl decision, they were for GRP $\sigma_\theta^{\max} = 163.5$ MPa and $\sigma_\psi^{\max} = 93.5$ MPa and for CRP $\sigma_\theta^{\max} = 270$ MPa and $\sigma_\psi^{\max} = 155$ MPa.

Analysis of obtained data leads to the conclusion that not taking the variable casing thickness into account can lead to the errors in dangerous direction, which equals to: $\sigma_\theta^{\max} - 11.6\%$, $\sigma_\psi^{\max} - 9.22\%$ for GRP and $\sigma_\theta^{\max} - 7.21\%$, $\sigma_\psi^{\max} - 8.28\%$.

4. Conclusions

Refined method for evaluation of SSS components of toroidal pressure hulls of underwater technical devices, which takes variable thickness at transverse winding combined with longitudinal winding (or facing) is developed.

Numeric analysis of obtained results convergence shows that for evaluation holding of $M = 5$ row members is enough, and for flexures $M = 3$ is enough.

Maximal flexure is developed at $\theta = \pm\pi/2$ and equals to 17% of variable casing thickness for GRP and 16.3% of it for CRP. All middle line points are displaced in the direction of geometric center of casing intersection, excluding the narrow area around point A ($\theta = \pi$). Maximal normal stresses are observed at $\theta = \pi$, and at $\theta = \pm\pi/2$. Maximal bending moments are observed at $\theta = \pm\pi/6$.

It is shown, that taking variable thickness during transverse layers winding and transverse winding combined with longitudinal winding (or facing) into account causes the significant impact on the value and distribution of evaluated stresses on the meridian intersection, if compared to the evaluation by an averaged thickness. Not taking the variable thickness into account leads to the errors, which are directed into the dangerous direction.

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VISUALIZATION FLOW ON THE PELTON TURBINE BUCKET BY CFD

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Abstract: In this study, series of CFD simulation were carried out for two phase flow (free surface), three dimensional geometry and turbulent flow through the pelton turbine. The present investigation employed on the pelton turbine bucket models various splitter angle and inlet velocity values for visualizing the flow pattern and identifying the force on the bucket. In this study, Two different bucket models were applied at different inlet velocity (20, 25, 30, 35 and 40 m/s) and four different splitter angle (55, 75, 90 and 115) for finding the effect of every single parameter on the effective force on the bucket. The obtained results discovered that there is a linear relationship between force and inlet velocity on the bucket. It uncovered that relationship between splitter angle and force on the bucket is linear until 90 degree after that this relationship is a non-linear.

Keywords: CFD, PELTON TURBINE, FREE SURFACE FLOW, VOF, BUCKET DESIGN

1. Introduction

The most commonly used turbine for high head power plant is Pelton wheel. Because of change of impulse (momentum) of moving water as opposed to its weight like traditional overshot water wheel, The Pelton wheel extracts energy. Even though deviations of impulse turbines presented prior to Pelton design, they were less effective than Pelton's design, the water leaving these wheels typically still had high speed, and carried away much of the energy.

Thus, all engineers, designers and researchers try to obtain high efficiency by adjusting the bucket and nozzle. This research applied two different bucket models of the pelton turbine for identifying the visualization fluid flow and force on the bucket by modifying several working conditions and geometrical parameters. An example of working conditions is the inlet velocity which affects the force and visualization fluid flow. Furthermore, the instance of the geometrical parameter is the splitter angle between nozzle and bucket which impacts the value of the force on the bucket of pelton turbine. The jet of circular cross section is distributed from nozzle and transfers in air before striking the bucket in Pelton turbines. The bucket is separated into two symmetrical semi ellipsoidal cups via a sharp edge splitter. The jet strikes the bucket on the splitter. The jet is alienated into two similar sheets of water having free surface which transfers on the curved path of bucket by the splitter. The profile of curved path of bucket impacts the force, pressure and velocity distribution over bucket. For instance, only Kvicinsky, S., 2002, compared the calculated pressure distribution experimentally. However, another researcher applied a stationary pelton turbine bucket as water impinged it experimentally Grozev et al 1988. The present investigation implemented computational fluid dynamic and some CFD models like VOF model and K-epsilon model. Several researchers examined the steady bucket like Janetzky et al., 1998. The coming out water of the nozzle is circular in cross-section. The water jet moves liberally in air and executes on a bucket of the runner thus rotations occur. For better comprehending the flow, Visualization was helpful. The results demonstrated at the end of this examination, are utilized for providing vision into the benefit we can expect of stable-state calculations of the flow throughout the universal process of pelton design optimization.

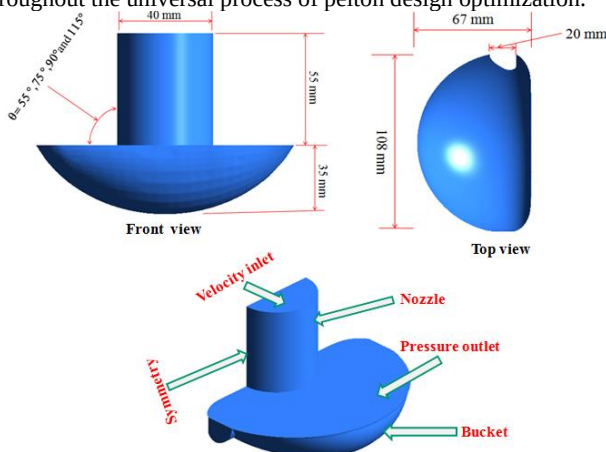


Figure 1. Solution domain and boundary conditions of the model 1.

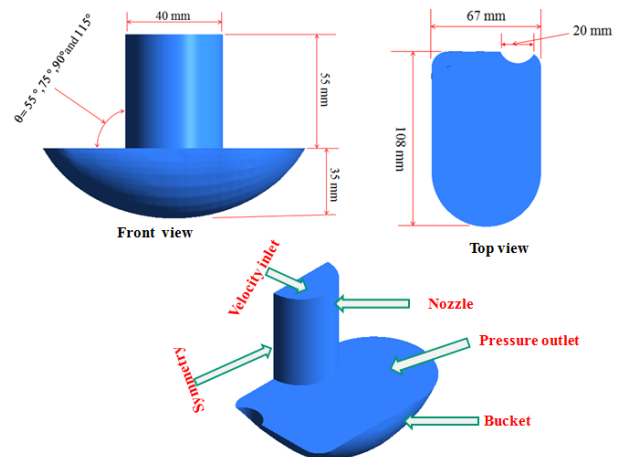


Figure 2. Solution domain and boundary conditions of the model 1.

2. Materials and Methods

This investigation applied ANSYS Workbench to generate the bucket of pelton turbine geometry as indicated in Figure 1 and 2. Specifically, Design Modular module of ANSYS was utilized. Concisely, in this work two different models were investigated and both models had 50% width of the bucket and diameter of the nozzle of 67 mm and 40 mm correspondingly. The influence of force on bucket pelton turbine shapes and visualization fluid stream on the bucket was evaluated in this examination. In this study four various splitter angle (55, 75, 90, and 115 degree) and different inlet velocity (20, 25, 30, 35 and 40 m/s) were employed. Grounded upon mesh independence test, the volume of a highest mesh was determined. The minimum mesh size was set to be less than the first layer thickness close to the wall and the lowest mesh sizes were determined to be 0.000019 m to avoid incorrect automatic mesh generation in the solver. Figure 3 and 4 illustrated the full size of mesh elements for both models. The right and left sides of the domain were identified as pressure outlet and velocity inlet respectively. Figure 1 and 2 demonstrated that when the computational domain was generated, top and bottom sides were wall. In this research, For determining force on the bucket and visualization of the flow computationally, the commercial software ANSYS FLUENT was applied.

The sweep method is a new technique in ANSYS-FLUENT utilized for capturing the free surface flow profile of flow. It can be reported that higher mesh gives force on the bucket to be 3319.6 N rather than escalating number elements do not affect the accuracy. By the way, the difference in the mesh independent test can be up to 4 % or 5% relying on nature of the issue which demonstrated in table 1. The aim of this technique is to refine the mesh size along the direction normal to the flow direction.

Table 1. Denotes Investigation of mesh dependence.

Number of element	Force on the bucket(N)	Difference (%)
331694	1310	2.6
658152	1324	1.56
966322	1335	0.74
1299188	1345	0

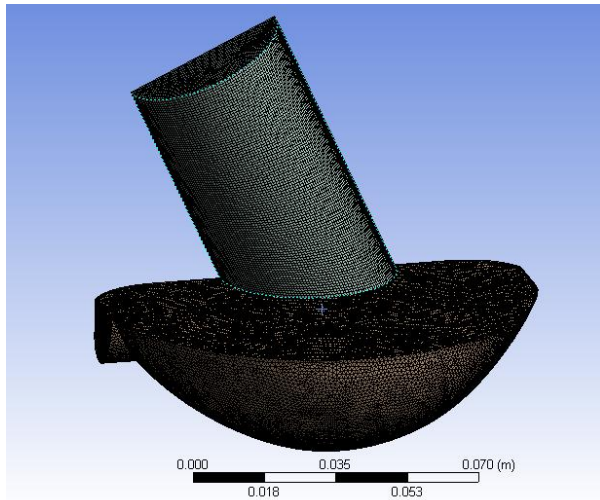


Figure 3. Computational mesh for Model 1.

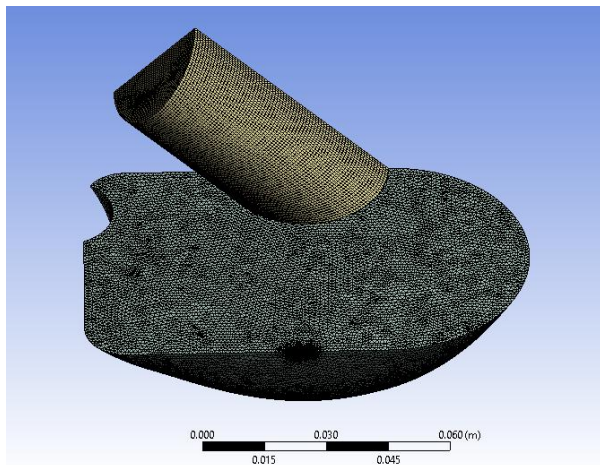


Figure 4. Computational mesh for Model 2.

Mathematical model and equations utilizing of Reynolds number;

Must be known to determine the regime of flow turbulent or laminar. The characteristic length of geometry, average velocity and fluid properties are effecting the transition from laminar flow to turbulent flow. Generally, Re can be expressed as for two phase flow.

$$Re = (\text{Inertial forces}) / (\text{viscous forces}) = VD/v = \rho v L / \mu \quad (1)$$

μ Viscosity of fluid.
 ρ Density of fluid.
 L length
 V velocity of fluid

The governing equations of viscous flow are based on conservation of mass, momentum and energy which are langrangian in nature. The governing equations are expressed using equations .

$$\text{Conservation of mass } \partial \rho / \partial t + \rho \nabla \cdot \mathbf{V} = 0 \quad (2)$$

$$\text{Conservation of Momentum } \rho D\mathbf{v}/Dt = \rho \mathbf{g} + \nabla \cdot \boldsymbol{\tau} - \nabla p \quad (3)$$

$$\text{Conservation of Energy } \rho Dh/Dt = Dp/Dt + \nabla \cdot (K \nabla T) + \Phi \quad (4)$$

3.Result and Discussion

The Effect of outlet Pressure

Hydraulic design in both a single flow and two-phase flow systems is extremely impacted by pressure. In the present examination, pressure gauge is a substantial element for determining outlet boundary pressure particularly in the pelton turbine. Pressure is an important element in characterizing the flow condition and designing the bucket. At the beginning pressure was high then it declined progressively at the edge of the bucket. Pressure was generated on the bucket as the water crushed from the nozzle to the bucket. The impact of high jet resulted in the pressure distribution in the bucket. Jet strike was increased at the inlet velocity because of the pressure distributions on the bucket. The water volume fraction contour clearly demonstrate the water strike on the bucket. As illustrated in figure (5), once the Reynolds number was 1194017.9 and splitter angle was 115 of the model 1 highest force and pressure on the bucket was 2230.7N and 922141.4 Pascal correspondingly. These outcomes are similar to findings of (Gupta and Prasad, 2012) and (pellone and maitre 2006).

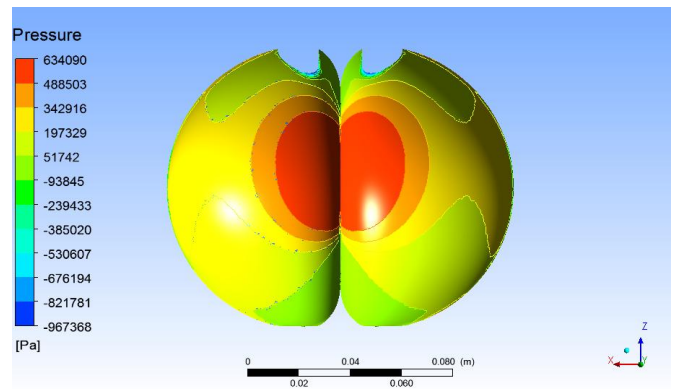


Figure 5. Variation of pressure when the splitter angle = 115 degree and velocity = 30 m/s of the model 1.

Figure (6) displays that by applying the Reynolds number was 1194017.9 and splitter angle was 115, the highest force and pressure on the bucket was 2442N and 899829.6 Pascal correspondingly in the model 2. Pressure is an important component for designing and characterizing the flow condition of the bucket. The water crush on the bucket is evidently demonstrated in water volume fraction. Owing to the pressure distributions on the bucket, Jet strike was escalated at the inlet velocity. At the beginning pressure was high then it declined progressively at the edge of the bucket. The effect of high jet caused the pressure distribution in the bucket. Pressure was generated on the bucket as the water crushed from the nozzle to the bucket. These findings agree with (Gupta and Prasad, 2012) and (pellone and maitre 2006).

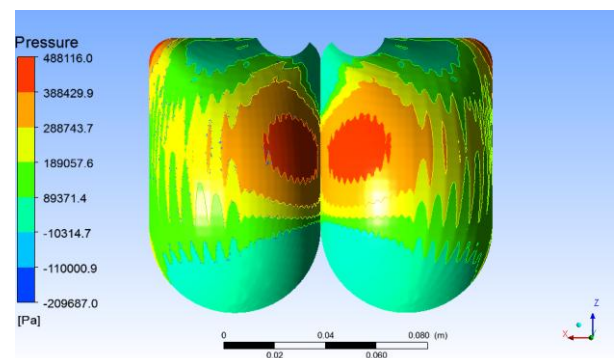


Figure 6. Variation of pressure when the splitter angle = 115 degree and velocity = 30 m/s of the model 2.

Water volume fraction

Water volume fraction contour illustrates the water phase and air phase on the bucket. As the flow is a turbulent in this examination, the water volume fraction is highly significant for the boundary impact of the pressure and force on the bucket. Therefore, the modification of the splitter angle resulted in change of the shape of the boundary. In general, red color represents a water phase, when the boundaries effective of highest pressure and big force on the bucket. Furthermore, the rain bow color demonstrates water and air phase as mixture. Moreover, the blue color displays an air phase which is not under pressure and force. It is observed from figure (7) when Reynolds number was 1194017.9 and splitter angle was 115 of the model 1 the highest force on the bucket was 220.7 N and pressure was 922141.4Pascal.

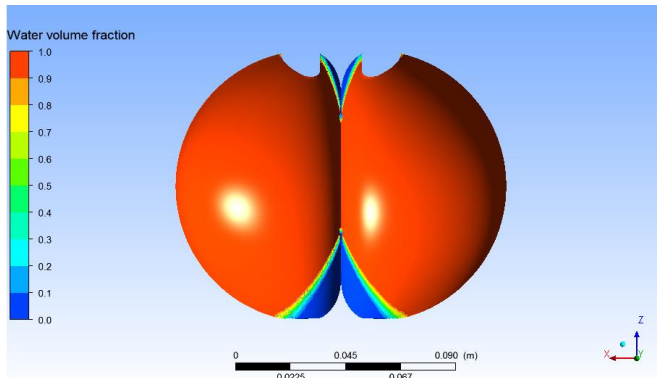


Figure 7. Water volume fraction when the splitter angle = 115degree and velocity =30 m/sof the model 1.

Generally, the blue color indicates an air phase which is not under pressure and force. Furthermore, when the boundary effective of highest pressure and big force on the bucket, red color demonstrates a water phase. Besides, the rain bow color demonstrate water and air phase as mixture. The water volume fraction is extremely important for the boundary effective of the force and pressure on the bucket because the flow in this study is turbulent. In the model 2, as illustrated in figure (8), When Reynolds number was 1194017.9 and splitter angle was 115 the highest force and pressure on the bucket were 2442N and 899829.6Pascal correspondingly. The Water volume fraction contour demonstrates the air phase and water phase on the bucket. Consequently, the change of the form of the boundary is resulted from alteration of the splitter angle. These findings agree with (Gupta and Prasad, 2012).

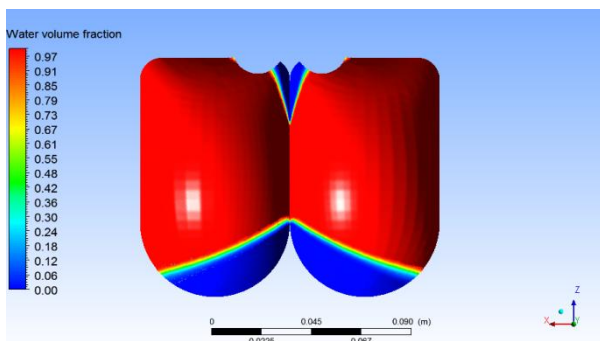


Figure 8. Water volume fraction when the splitter angle = 115degree and velocity =30 m/sof the model 2.

Velocity vector

It is the direction of the velocity similar as the velocity magnitude. It demonstrates the proportion of the change of the fluid position. Velocity vector is the maximum compared to the velocity in all position in the bucket of the pelton turbine.

As demonstrated in vector pattern, the jet has parallel vector lines before crushing the bucket. Owing to deflection of jet, the

vector lines spread near the bucket. The jet spread, after striking the bucket. It can be seen that the velocity at the inlet was high then decreased gradually, as displayed in figure (9). Once splitter angle was 115 Reynolds number was 1194017.9 and of the model 1, the biggest force on the bucket was 2442N. These findings agree with (Gupta and Prasad, 2012). Without the participation to impulse force, it was monitored that higher amounts of water leave throughout the cut-out which result in wastage.

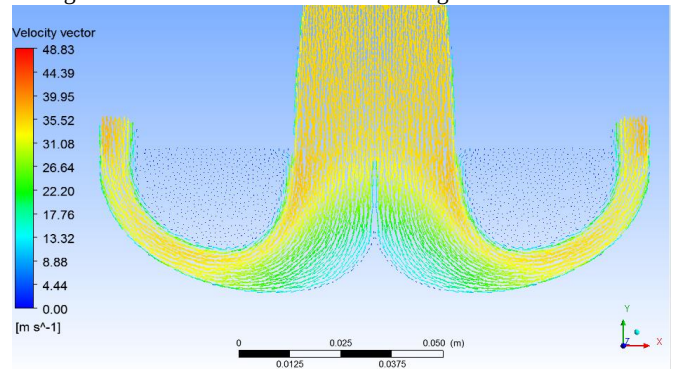


Figure 9. Shows velocity vector when the splitter angle = 115degree and velocity =30 m/sof the model 1.

Due to deflection of jet, the vector lines spread nearby the bucket. High velocity was observed at the inlet however it declined progressively in figure (10). The jet has parallel vector lines before crushing the buckets displayed in vector pattern. Without the participation to impulse force, it was monitored that higher amounts of water leave throughout the cut-out which result in wastage. The jet spread, after striking the bucket. In the model 2, the maximum force on the bucket was 2442N as splitter angle was 115 and Reynolds number was 1194017.9. These outcomes are similar to (Gupta and Prasad, 2012).

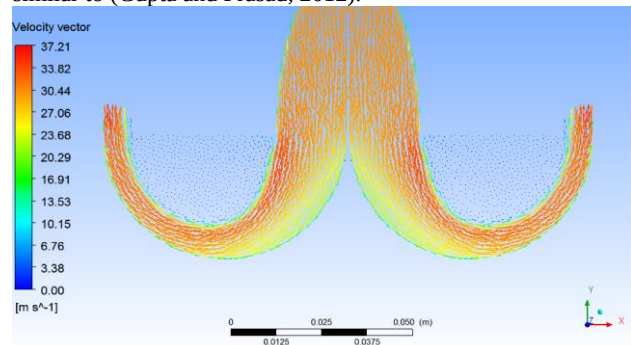


Figure 10. Shows velocity vector when the splitter angle = 115degree and velocity =30 m/sof the model 2.

The figure (11) displays that the study's outcomes are very close to the journal result. This is true when the fluid, model and geometries were the same. For finding the correct model for this research, this comparison has conducted. This journal has been chosen for discovering the accurate models for this research because it is close to our investigation. The results of both researches are close to each other. Thus, it can be stated that the model of this research is accurate.

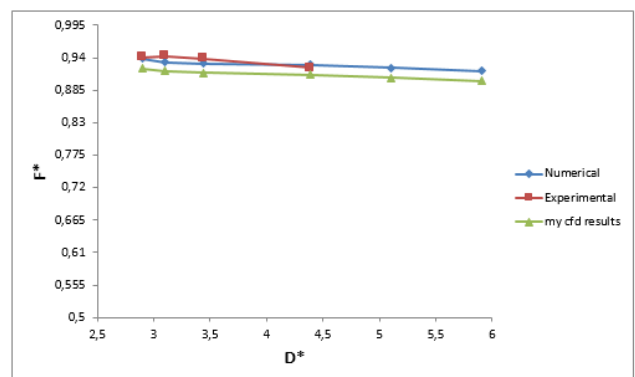


Figure 11. Shows the difference between my CFD result and journal papers result (zoppe et al., 2006).

When the splitter angle is 115 degree, the correlation between Reynolds number and the maximum Force on the bucket is displayed in the Figure (12). It is visible from the figure that relationship between the maximum force on the bucket and Reynolds numbers is positive. This means that the maximum force on the bucket increased steadily by increasing the Reynolds number. It can be seen that a Reynolds number 1592023.9 results in a maximum force on the bucket of 3972 N. In addition, when the Reynolds number is 796011.96, the force on the bucket is 992.8.

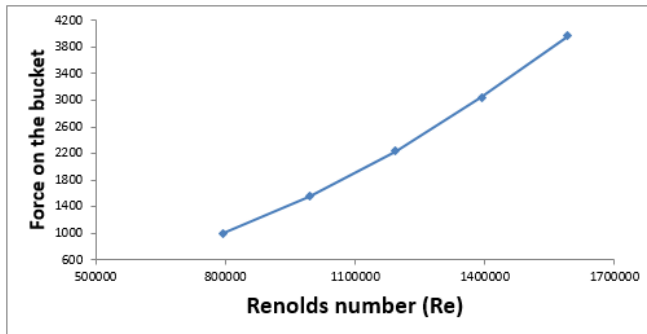


Figure 12. Influence of the Reynolds number on force when the splitter angle 115 deg of model 1.

4. Results

In high head and low water stream, the Pelton turbine was performed because it is simple construction and ease of manufacturing. The turbine parameters have to be included in the designing process for obtaining a Pelton hydraulic turbine with the maximum efficiency different working circumstances. The ANSYS-FLUENT was applied for the simulations of liquid flow. The VOF CFD models were employed for the two different models of the bucket. The results of pressure contour, stream line velocity, and force on the bucket, water volume of fraction and velocity vector were obtained from CFD simulations models. The simulation of visualized stream on the bucket and determined a force on the bucket in pelton turbine for four different inlet velocity (20, 25, 30, 35, and 40 m/s) for both models. Moreover, four different splitter angles (55, 75, 90 and 115 degree), were utilized for both models. In the present study, two diverse bucket models were implemented at different inlet velocity (20, 25, 30, 35 and 40 m/s) and four diverse splitter angle (55, 75, 90 and 115) for discovering the effects of every parameter on force on the bucket. It was revealed there is a linear relationship between inlet velocity and the force on the bucket. The examination revealed that until 90 degree, the relationship between splitter angle and force on the bucket is linear. However, subsequent the 90 degree, there was a non-linear relationship.

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ENVIRONMENTAL IMPERATIVE OF INNOVATIVE INDUSTRIAL PRODUCTION

ЭКОЛОГИЧЕСКИЙ ИМПЕРАТИВ ИННОВАЦИОННОГО ПРОМЫШЛЕННОГО ПРОИЗВОДСТВА

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Abstract: *The parallel functioning of strategies for innovative and sustainable development leads to the emergence of a formal methodological paradox in the form of increasing negative technological impact on the environment due to the prevalence of economic criteria for assessing the efficiency of production over social criteria. This paradox determines the permanent growth of products that can be combined with the concept of waste. To eliminate the methodological paradox, it is necessary to implement the ecological imperative by greening the legal framework that regulates all stages of the life cycle of innovative products.*

KEYWORDS: INNOVATIVE DEVELOPMENT, TECHNOGENIC IMPACTS, ENVIRONMENT, WASTE CONCEPT, ENVIRONMENTAL IMPERATIVE

1. Introduction

The development of the global economic system and its various components (supranational, state, federal, etc.) is carried out with the combined effect of innovation and sustainable development strategies. The specific contribution of each strategy to the development of an economic system of a specific type is determined by a combination of key factors: material, technological, personnel, organizational, regulatory legal [1-10]. The value of application (implementation) of the basic principles of the sustainable development strategy in a really functioning system that determines the effective, safe and comfortable functioning of societies is one of the most important features that determine the prospects of a progressive socially oriented system of functioning of economic structures of various subordination, function, form of ownership [14].

Effective application of cumulative intelligence formed in various spheres of society activity allows integrating the positive signs of dynamically developing business entities with a permanently growing volume of production and an expanding range of marketable products in order to ensure sustainable growth in profitability and the basic signs of the practical implementation of sustainable development strategies that manifest themselves in increasing the share use of raw materials in the final product, a decrease in specific energy, upgrading of technologies at all stages of production and application that make possible the minimization of negative anthropogenic impact on the environment.

An important role in the production functioning of economic systems at all levels of the organization belong to current regulatory legal documentation [12]. At the same time, special attention was paid to the sphere of waste management, because the practical implementation of strategies for the sustainable development proposes the prevention and minimization of negative anthropogenic impact on the ecosystem. In this impact the material and energy components determined by the definition of "waste" have a dominant role.

The effectiveness of improving the management system and the legal framework for the management of waste and its law enforcement is determined by methodological approaches to its formation on the basis of current trends, the development of production infrastructure adequate to the overall requirements of a strategy of sustainable and innovative development.

A large number of studies have been devoted to the problem of normative legal support for the practical implementation of the basic principles of a sustainable development strategy [1-9]. At the same time, there is a need to improve methodological approaches to the development of a legislative framework and its effective enforcement, aimed at translating the principle of "greening" legislation [13].

2. Research methods

For the research we used a systematic analysis of the production, organizational, legal, administrative, social and environmental factors of the operation of economic systems.

As an object of research we used an industrial enterprises of the Grodno region, which produce products for various purposes.

3. Results and discussions

Analysis of the concept-categorical apparatus used in the legislation of the countries of Commonwealth of Independent States (CIS) that regulates the sphere of waste management [1-9] testifies to the traditional concepts of participants in the economic activity (the sphere of production) and members of societies (the sphere of consumption) about the predetermination and inevitability of the process of the formation of material substances, combined waste definition. Meanwhile, the essence of the process of waste generation lies in the initial implementation of a sound technological impact on raw materials, semi-finished products, components, which leads to the formation, on the one hand, of products not used in the final result of labor – products ("production waste"), and on the other – creates the prerequisites for the subsequent destruction of this product at the stages of transportation, storage, operation and maintenance, i.e. the emergence of "consumer waste". This circumstance makes it possible to use, in place of the notions of "production waste" and "consumption waste", the generalized concept of "industrial waste", which combines the concepts "production waste" and "consumption waste" within the "product life cycle" and allows the development of approaches to prevent or reduce the probability the formation of waste products in the form of products of destruction, wear, corrosion damage, aging and other effects of operational factors acting on products obtained in the process of directed technological impact by optimizing stage of marketing research, development, production design, testing and certification, warranty and after-sales service systems.

The current technological paradigm focuses on the parameters of characteristics of consumer properties of commodity products, rather than parameters characterizing the amount of waste and their activity in the negative impact on the environment. This aspect underscores the need for systematic improvement of the current normative legal technical documentation in terms of increasing the level of responsibility for the quality parameters of the products and the quality parameters of the technological operations used, estimated according to the criteria of resource intensity, "low-waste" and environmental safety in various forms.

It goes without saying that "environmental problems are not problems of the environment but in their genesis and consequences entirely social problems, human problems, its history, conditions of its life, its relation to the world and reality, its economic, cultural

and political views "[10, P. 336]. According to N. N. Moiseev [11] "... the strategy of the development of mankind has two components:

1) scientific and technological: in the shortest possible time to reduce our needs, which should reduce the burden on the biosphere;

2) moral-social – "ecological imperative", which includes a variety of environmental properties, the changes of which human activity can not be permissible under any conditions» (are noted by us – S.A., A.O., B.A.) [10, P. 337].

The implementation of the environmental imperative in real economic systems is a multifactorial problem. System analysis of possible directions for solving the problem of handling industrial waste testifies to the prevailing importance of the economic factor causing a permanent inefficiently regulated growth in the industrial production of marketable products of various functional purposes, including with the predominant use of traditional (routine) technologies, equipment that are largely unoptimized (unfinished) processes, leading to an increase in total waste weight in general used raw materials, intermediate products and auxiliary materials. A significant part of the traditional technologies mismatch the requirements of the state energy and resource saving strategy, but it is used because of the existing system of functioning of economic systems within the legal framework that does not take into account the current trends in the sustainable development strategy.

Therefore, as A. Moskvina rightly pointed out, the most important factor of the progressive negative man-made effect on the environment is the fact that "... at the present stage of development in the world economy technologies of incomplete consumption dominate (are noted by us – S.A., A.O., B.A.), built on the principle "to extract the most valuable and discard all unnecessary" (are noted by us – S.A., A.O., B.A.) [15]. The vulgar understanding of progressive economic development as a process with a permanent increase in the volume of production and the nomenclature of commodity output, which dominates the world economic system, "degenerates into a systematically unremovable economic defect: the production and use of a commodity product is accompanied by the production of unclaimed wastes" (are noted by us – S.A., A.O., B.A.) [15]. At the same time, the excess production of marketable products in accordance with the concept of maximum satisfaction of needs is actually the production of complex waste that requires the use of expensive special recycling technologies, the use of which is a negative factor in the economic development of state structures.

A formal paradox is formed in the organization of the life activity of societies of various levels, which consists in the economic, technological (production) and consumer (social) conditionality of the process of formation of unclaimed or excess (residual) quantities of substances of different composition, structure and conditions of formation at the stages of extraction, mineral, artificial and synthetic materials that are products of geochemical, chemical or biochemical processes, processing and consumption of commodity products for various purposes, which are united by the category "waste".

The existing paradigm of the production activity of economic entities is based on the primacy of the normative technical documentation (design documentation, technological processes and regulations, technical conditions, industry and technical standards) that regulates the production of items with specified quality parameters and functional consumer characteristics, in relation to the normative legal documentation that defines parameters of environmental safety of the production process, application of various products values and their recycling after depreciation. This aspect causes a certain delay in the development of modern legal provisions in the field of the ecological (sustainable) functioning of industrial production and the effective management of waste generated at different stages of activity of economic systems and societies of consumers of marketable products. Meanwhile, as stated in [16] "... at the first stage of social and economic development for the transition to sustainable development ..." it was assumed that "... the creation of the necessary legislative and legal framework for sustainable development must be completed ..." [16, P. 28].

Therefore, for the developing a methodology of regulation the modern distribution chain of waste of various chemical composition, structure, prehistory of formation, a systematic approach is needed. This approach must be combine the basic socially-oriented principles of supranational and state acts with realities the functioning of specific economic entities that support the life of social groups by creating jobs with guaranteed security conditions and adequate material, technical, technological and financial both baking. The good approach to solving this multifaceted problem is the concept of "greening the legislation" proposed in [13, P. 223], by which "... the inclusion of environmental and legal requirements in the content of regulatory legal acts of other branches of law (civil, administrative, criminal, financial, tax, etc.) ». Thus, "greening regulations (are noted by us – S.A., A.O., B.A.) represent the regulations of other branches of law that regulate ecological relations in conjunction with proper environmental standards" [13, P. 223].

4. Conclusions

The currently dominant concept of the development of the global economic community, focused on the maximum satisfaction of the constantly growing uncertain demand and excessive consumption of marketable products, while maintaining the traditional principles of developing a regulatory framework regulating the relationship of societies and individuals with ecosystem components at all levels of organization and functioning, stipulates permanent progressive growth of negative impact on the ecosphere of rapidly growing sizes of ineffective processing of raw materials, the availability of which is not particularly limited, and amortized unclaimed (unsold) products and social communities of waste products of all kinds. In this aspect, the implementation of the environmental imperative by "greening the legislation" in the sphere of commodity circulation is, in our opinion, effective and, in some cases, a non-alternative direction for the practical implementation of the sustainable development strategy for regional and world societies with a socially oriented innovation economy.

Formed on the basis of the "paradox of abundance" concept the economy does not take into account the progressively growing environmental damage not only to a particular region, but also to the global economy as a whole. In this aspect, the most significant is the preventive function of environmental enforcement, which aims not to minimize the adverse environmental impact of functioning economic entities, but to create a well-founded and controlled counteraction to the very process of the emergence of such economic entities with incomplete (imperfect) technological production cycle, creating the prerequisites for education significant quantities of material components, positioned as a "technologically unavoidable" or "technologically grounded" waste [14]. Practical implementation of the environmental imperative by "greening the legislation" is a multifaceted problem, including educational, organizational, technological, research, economic and other factors.

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ANALYSIS AND FRACTURE OF ALUMINIUM ALLOY COMPONENTS USED FOR SPINNING OF CHEMICAL FIBER

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Abstract: An aim of a research was to determine the reasons of fracture of aluminium alloy components used for spinning of chemical fibres and to improve spinning process by selecting material with better performance.

Keywords: ALUMINIUM ALLOY, FRACTURE, MICROSTRUCTURE

1. Introduction

The purpose of the aluminum alloy rods used by a producer of chemical fibers is to tighten and direct the fiber spun on the reel (Fig. 1). During the operation, the rods are constantly vibrating, i.e. cyclically loaded. In the event of a break, the part should be replaced by a new one, therefore the downtime occurs in production of chemical fiber.

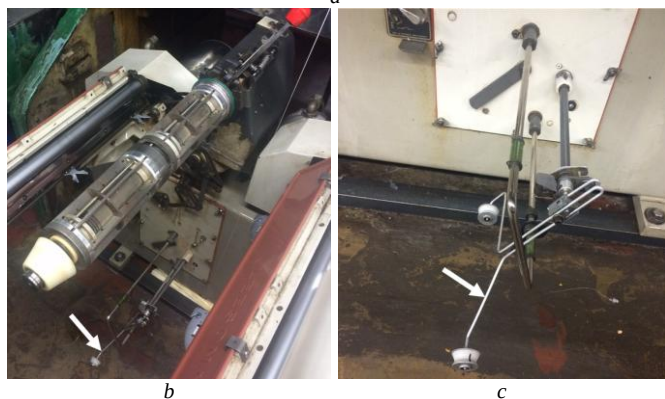


Fig. 1 Spinning machines for production of chemical fibers: a) general view; b) workplace of spinning on reel; c) fiber tensioner made of aluminum alloy. White arrows show tensioners investigated

The producer decided to decrease the risk of the downtimes by choosing material with better performance for the parts.

The aim of the work was to analyze the reasons of fracture of the parts and to choose other aluminum alloy which could maintain more cycles of vibrations during the production of chemical fibers.

2. Methodology

Determination of chemical composition and analysis of mechanical properties showed that the current tensioners have been manufactured from the rod of aluminum alloy 6061 (according to EN) (1 and 2 Tables).

Chemical composition was determined according LST CR 10320-2006 standard by optical emission spectrometer ARC-MET 8000. Tension strength and yield point were examined according

EN ISO 6892-1:2009 standard in Tinius Olsen H50KT universal testing machine.

Table 1: Chemical composition of aluminum alloy used for current tensioners (% wt)

Sample	Elements, %								Equivalent of alloy grade
Rod Ø3 mm	Al	Si	Mg	Cu	Mn	Zn	Ni	Fe	6061 (AlMg1SiCu)
	Bal.	0.695	1.07	0.293	0.089	0.015	0.005	0.207	
	Pb	Bi	Cr	Ti	Sn	V	Ca	Be	
	0.005	--	0.165	0.011	0.022	--	0.007	0.014	

Table 2: Mechanical properties of current tensioners material

Dimensions of sample	R_m , MPa	$R_{p0.2}$, MPa	A, %	Z, %
Ø3 mm × 50 mm	408	321	21.5	50

The fracture surface and microstructure of aluminum alloy used for the current tensioners was examined by optical microscope optical microscope Nikon equipped with video camera Nikon DS-2 16 MP and objectives Nikon TU Plan Fluor 10×/0.30 and Nikon TU Plan Fluor 100×/0.90.

Trying to order different grades of aluminum alloy it was found out that in the producer's area just two grades were available – 6060 and 6063. Therefore, these two grades were compared with the current one seeking to choose the material with better performance.

3. Results and Discussion

3.1. Analysis of chemical composition of system Al-Mg-Si

According to EN standards, the 6XXX numbering indicates that these are heat treatable wrought alloys of Al-Mg-Si system, which are also found in the literature under the name of "avials" (aviation alloys) [1]. Avials are low-alloyed with magnesium and silicon (sum of alloying elements 1-2%); these alloys also contain small additives of chrome and manganese. By forming the dispersed phases of Mg_2Si , Al_6Mn , Al_7Cr , alloying components decrease the grain size microstructure and raise the temperature of the recrystallization. Copper addition increases the strength of avials, but reduces the corrosion resistance of the alloys [2]. Al-Mg-Si alloys are deformable – their properties can be improved by heat treatment and deformation.

In order to find as much information as possible about the alloys of interest, German and Russian aluminum alloy analogues were also reviewed (Table 3). The equivalent of the aluminum alloy 6063 was not found in DIN or GOST standards.

The chemical composition of the aluminum alloys is regulated by the European Union standard EN 573. The chemical composition of alloys is given in Table 4, which is comparable to the currently used grade.

Table 3: Aluminum alloys equivalents

EN 573		DIN 1712, 1725		GOST 11069, 4784	
No.	Grade	No.	Grade	No.	Grade
6060	AlMgSi	3.3206	AlMgSi0.5	1310	A/I31
6061	AlMgSiCu	3.3214	AlMg1SiCu		A/I33
6063	AlMg0.7Si	-	-	-	-

Table 4: Comparison of aluminum alloys chemical composition (according DIN EN 573-3:2009-08) [3]

Alloy	Si	Fe max	Cu max	Mn max	Mg	Cr max	Zn max	Ti max	Al	Other	Impurity	
											Max of each	Total
6060	0.3-0.6	0.1-0.3	0.1	0.1	0.35-0.6	0.05	0.15	0.1	Bal.	-	0.05	0.15
6061	0.4-0.8	0.7	0.15-0.4	0.15	0.8-1.2	0.04-0.35	0.25	0.15	Bal.	-	0.05	0.15
6063	0.2-0.6	0.35	0.1	0.1	0.45-0.9	0.1	0.1	0.1	Bal.	-	0.05	0.15
Currently used alloy												
6061	0.695	0.207	0.293	0.089	1.07	0.165	0.015	0.011	97.50	0.005Ni 0.005Pb 0.022Sn	-	-

3.2 Alloying of system Al-Mg-Si

Magnesium increases the strength of aluminum alloy. One percent magnesium increases tensile strength R_m by about 30 MPa. Magnesium increases the vibrational durability of the alloy, as well. The grade 6061 has the maximum magnesium content and the grade 6060 has the lowest content.

Silicon forms reinforcing phases inside the microstructure of the alloys, i.e. compounds of Mg_2Si . These particles are several micrometers in size or smaller; hard, strong, in alloys acting as a reinforcing material. 0.5-0.6% of silicon improves welding performance. According to the EN standard, the maximum content of silicon is in the 6061 alloy, in comparison of three grades investigated.

Manganese and chromium increase the strength of alloys. Alloys of Al-Si-Mg system that contain these elements become hardened by highly dispersed phases [Al_6Mn , α -(Al-Si-Mn), Al_7Cr], which increase the temperature of the recrystallization of plastically deformed products and inhibit grain growth. In the 6061 alloy, the amount of manganese and chromium is allowed maximum, in the second place is 6063, and in the third – 6060.

Zinc, titanium and chromium reduce the possibility of corrosion under stress. In addition, just 0.4-0.8% zinc increases the yield strength of the aluminum alloy.

The small amount of copper that occurs in the alloys investigated, and is almost all dissolved in the solid solution, slightly increases the strength of it, but its higher content (0.05-0.1%) decreases resistance to corrosion, especially intercrystalline.

The iron impurity has the most degraded effect to aluminum alloys – it practically does not dissolve in aluminum, but forms fragile intermetallic phases, therefore, the amount of iron has to be as small as possible. According to standard EN 573, the maximum iron content in alloy 6061 may be up to 0.7%, but only 0.207% was found in the currently used alloy according to the chemical composition analysis. In alloys 6060 and 6063, the iron content is more restricted to 0.3-0.35%.

3.3 Mechanical properties and heat treatment of Al-Mg-Si alloys

The mechanical properties of aluminum alloys depend particularly on the chemical composition, but even more on the heat treatment of the alloy. During heat or thermomechanical treatment, the strength, hardness and plasticity of aluminum alloys can vary a few times. The most common thermal treatment methods, labeled in accordance with EN 755:

- T4 – solid solution treated and naturally aged;
- T5 – cooled from an elevated temperature shaping process and artificially aged;
- T6 – solid solution treated and artificially aged.

After quenching, the aluminum alloy is in a state of a solid solution, which is saturated with dissolved alloying elements. Mostly plastic and soft. During the further aging, the excess of

alloying elements precipitates from the solid solution in the form of small particles (chemical compounds). These strengthening particles improves mechanical properties of the alloy. Aluminum alloys are most often treated for artificial aging (T6). The strength of the aluminum alloy is higher than after natural aging (T4).

The mechanical properties of aluminum alloys after different thermal treatment are regulated by standard EN 755. The characteristics of the mechanical properties presented in the standard are indicated by "the possible minimum". Maximum values of mechanical characteristics are not regulated. Table 5 shows the mechanical characteristics of the aluminum alloys investigated: tensile strength R_m , yield strength $R_{p0.2}$, relative elongation A and relative contraction Z.

Table 5: Comparison of mechanical properties of aluminum alloys (according EN 755-2:2016) [4]

Grade	Heat treat.	Diameter, mm	R_m MPa		$R_{p0.2}$ MPa		A %	A_{50} mm %	HBW
			min	max	min	max	min	min	
6060	T4	≤ 150	120	-	60	-	16	14	50
	T5	≤ 150	160	-	120	-	8	6	60
	T6	≤ 150	190	-	150	-	8	6	70
6061	T4	≤ 200	180	-	110	-	15	13	65
	T6	≤ 200	260	-	240	-	8	6	95
6063	T4	≤ 150	130	-	65	-	14	12	50
	T5	≤ 200	175	-	130	-	8	6	65
	T6	≤ 150	215	-	170	-	10	8	75
Currently used alloy									
6061		3	408		321		21.5	-	-

Comparing the properties of the investigated aluminum alloys, it is obvious that the highest strength corresponds to 6061 alloy, and the lowest – to 6060 alloy. Also, one can see how the strength of the alloys varies depending on the heat treatment method: the maximum strength is achieved after solid solution treatment and artificial aging (T6). However, the maximum plasticity after the same heat treatment corresponds to alloy 6063.

Mechanical properties of the material are usually characterized by the standard values R_m and $R_{p0.2}$. However, the high strength and yield limits sometimes show how the material will behave under the real conditions, especially when cyclical loads act. However, aluminum alloys showing high R_m and $R_{p0.2}$ values, do not exhibit significant strength. The reason of this can be the defects of the real product when operating under real conditions. The defects may include mechanical surface defects: cracks, scratches, surface roughness; metallurgical: oxides, rough intermetallic phases, chemical elemental heterogeneity. All defects in the material act as stress concentrators around which stresses may exceed the material's yield point or strength limit [5].

There are always cracks (or surface irregularities) on the surface of metallic components in real construction. Each material has its own period of slow crack propagation, during which the component can be operated. And only when the crack reaches a critical size, its further expansion occurs very quickly until a complete break. The fracture period during which the cracks develop slowly indicates the performance, functionality and durability of the product. This period may vary between different materials. Very often, materials with high mechanical characteristics R_m and $R_{p0.2}$, weakly resist the propagation of a crack, and materials with lower characteristics counteract much better.

The lifetime of the material can be assessed by the impact strength test. The higher the impact strength, the better the durability of the material. Unfortunately, the standard $5 \times 5 \times 100$ mm specimens are required to evaluate impact strength and therefore not suitable for wire.

The impact strength of an aluminum alloy can be increased in the following ways:

1. Reducing the amount of iron in the aluminum alloys. Best of all, when its content does not exceed 0.1-0.3%, and even better, when it is a hundred percentage points. Reducing the amount of iron, the amount of insoluble and very fragile intermetallic phases [Al₃Fe, α -(Al-Fe-Si), α -(Al-Fe-Si-Mn), etc.] reduces as well, resulting an increase of the impact strength of the alloy. Iron dissolves in aluminum up to 0.062%, all the excess is precipitated in fragile intermetallic phases.

2. By super-aging of aluminum alloys to ensure that coherent bonding that occurs between the matrix and the intermetallic phases become destroyed. According to EN standard, this would be a heat treatment method labeled by T7, i.e. the products are treated to a solid solution and super-aged (stabilized). The strength of these products is slightly lower than after the solution treated and artificially aged with the purpose to obtain the maximum strength (T6), but the impact strength of such treated alloys is higher.

3.4 Analysis of fracture and microstructure of aluminum alloy rods

A fracture analysis of the broken rod surface showed that the type of fracture is fatigue (Fig. 2). Fatigue fracture occurs in several stages. Metal decomposition starts with a defect on the surface – it can be corrosion-damage, crack, scratch, non-metallic insert, solid, fragile, intermetallic phase, etc. As the components investigated are loaded cyclically, the material's fatigue resistance and surface quality are very important. The origin of the fracture (surface defects), the propagation of the crack and the area of the final fracture are indicated by arrows. As the component is vibrating during exploitation, i.e. deformed in different directions, surface tensile stresses have induced the defects to propagate until the final break.

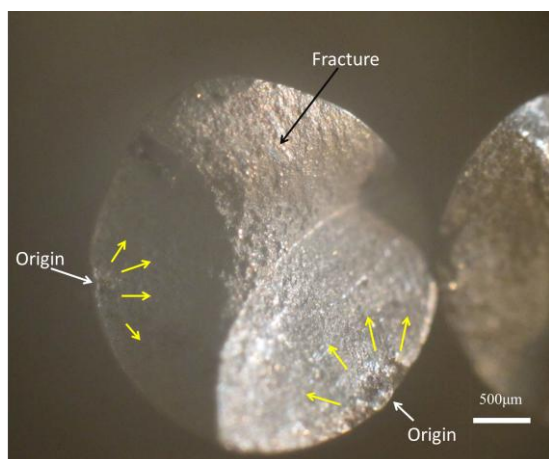
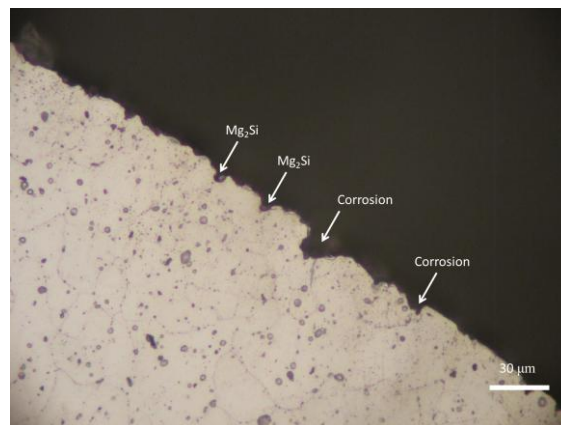


Fig. 2 Determination of fatigue fracture of the aluminum rod

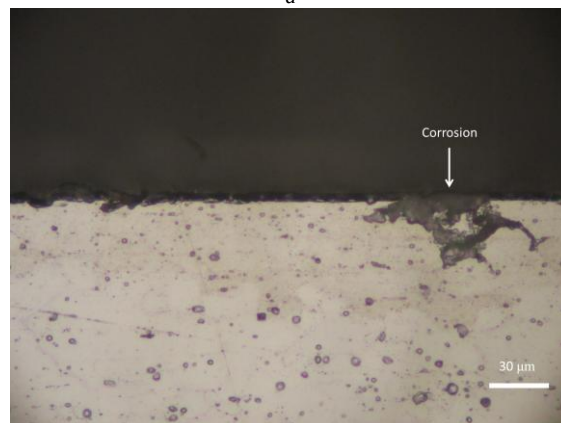
After microstructural analysis, it became obviously that the surface is rich in defects: possible corrosion damages, non-metallic inserts (Fig. 3). The amount of non-metallic inclusions was found to be a little; these inclusions would be the most damaging when accidentally appears at the surface.

A cross-section of the specimen was examined for the surface defects.

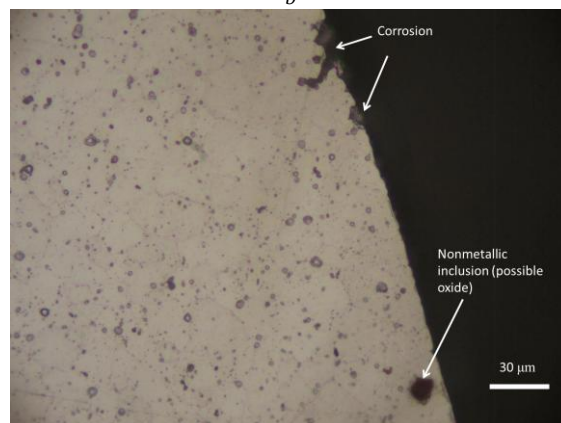
Deformable Al-Mg-Si alloys contain low amounts of alloying elements, usually the sum of all alloying elements does not exceed 1-2%. Aluminum alloys 6060, 6061 have a phase composition of α (solid solution) + Mg₂Si (hardening phase) [6], which is obtained after solution treatment and aging (artificially aging results higher mechanical properties than natural). Such a structure is visible observing the metallographic sample, made from the wire provided by the company (Fig. 4).



a



b



c

Fig. 3 Analysis of the microstructure of the broken aluminum rod: the defects found at or near the surface (a), (b), and (c)

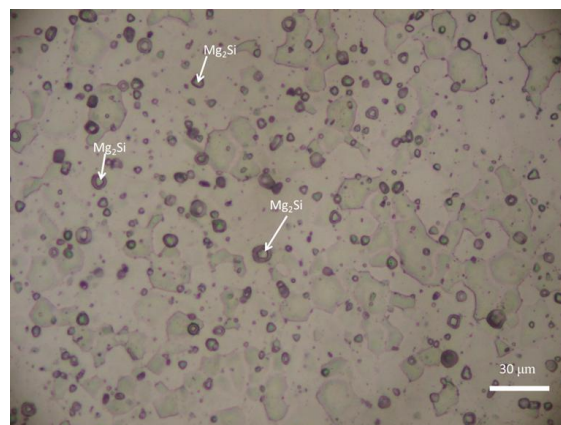


Fig. 4 Microstructure of currently used aluminum alloy: composition of solid solution and hardening disperse particles Mg₂Si

4. Conclusions

Following the investigation of the fracture and microstructure of the currently used aluminum rods and the literature analysis on Al-Mg-Si aluminum alloys, the following conclusions were formulated:

1. The cause of the breakage of the currently used aluminum rods is fatigue. If the suppliers of aluminum alloys provide information about the fatigue resistance, this characteristic should be taken into account.

2. Comparing the chemical composition of alloys 6060, 6061 and 6063, it is obvious that 6061 has a higher Mg and Si content, and these elements form hardening particles. Also, this alloy has a high content of manganese and chromium, which strengthens alloys. The second place according to the amount of alloying elements takes alloy 6063. 6060 alloy is the least alloyed aluminum alloy. Alloys 6060 and 6063 have more limited iron content than an alloy 6061, which can form fragile intermetallic phases. Also, alloys 6060 and 6063 have less copper, and therefore they are more resistant to corrosion. This is important because the parts are in an environment of increased corrosion.

3. Comparing the mechanical properties of alloys, the maximum strength and yield point presents the alloy 6061. The alloy 6063 stands at the second place. However, the alloy 6063 has a plasticity greater than 6061, therefore, considering the theory outlined in section 3.3, it is likely that the tensile strength of alloy 6063 will be sufficient.

4. Comparing the mechanical properties of alloys after thermal treatment, it is obvious that the maximum strength is achieved after solution treatment and artificial aging (treatment T6) During the heat treatment process, the alloying elements precipitate from the solid solution that strengthen the alloy.

Recommendation: From the two possible aluminum alloy grades 6060 and 6063, it was suggested alloy 6063 more alloyed by silicon and magnesium and presenting higher strength and plasticity (compared to 6060) after thermal treatment of T6.

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APPLICATION OF ECA PRESSING FOR THE PRODUCTION OF THE FUSE LINKS

ПРИМЕНЕНИЕ РКУ-ПРЕССОВАНИЯ ДЛЯ ИЗГОТОВЛЕНИЯ ВСТАВОК ПЛАВКИХ ПРЕДОХРАНИТЕЛЕЙ

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Abstract: The potential of using the ultrafine dispersion powder material obtained by the ECA pressing from a copper powder have considered for the production of fast-acting fuse links. The dependences of the density and microhardness along the length of the sample under different deformation conditions obtained. A deformation zone of constant density is determined and recommended for using in the production of fuse links. The dependence of the electrical resistance along the sample cross-section and across the deformation axis has determined. The fuse links calculation procedure has proposed.

KEYWORDS: BILLET, POROSITY, DEFORMATION, DENSITY, HARDNESS, MICROSTRUCTURE, ELECTRICAL RESISTANCE, FUSE LINK, FUSE.

1. Introduction

The equal-channel angular pressing allows production of bulk samples with a uniform ultrafine-grained (UFG) structure with a grain size of 100-200 nm and does not require complex equipment. There are three to eight passes needed to obtain a uniform UFG structure throughout the volume of billet, according to the results of most studies [1]. The UFG structure provides a substantial improvement in the mechanical properties of material [2]. At the same time, ECA pressing leads to the formation of a set of grain boundaries, which makes an influence on the material physical properties. As a result, such properties as electrical conductivity, coercive force decrease while increasing electrical resistance. Such physical dependences make it possible to recommend the material obtained by ECA pressing for parts with higher electrical resistance required.

The paper is aimed to study the potential of using the ultrafine dispersion powder material obtained by the ECA pressing from a copper powder have considered for the fabrication of fast-acting fuse links.

2. Research methodology

The stabilized PMS-1 grade copper powder has used for the experimental study. Prismatic billets of 0.5 x 0.5 mm in cross-section, 20 mm long, initial porosity 40%, 20% and 10% have produced by bilateral pressing on the hydraulic press model PD-476, force 1600 kN. The stepwise sintering was carried out in the synthesis gas medium. The deformation was performed in three passes using a special die tool for ECA pressing without removing the sample and changing the billet orientation [3]. The matrix had four prismatic channels of 0.5x0.5 mm, intersecting at 90° for ensuring continuity of deformation work. The inner curvature radius of the matrix channels was 1.0 mm, and the outer radius equal to zero. The compacting pressure was 480 MPa for the first pass and 550 MPa for the third while back pressure was 90 MPa [4].

Electrical resistance measurements of the samples obtained after ECA pressing in the longitudinal and transverse directions have carried out on a DC bridge device U39 designed for measuring electrical resistances from $1 \cdot 10^{-8}$ Ohm to $1,111 \cdot 10^8$ Ohm. The measurement error of the device has not exceeded 0.209%. To exclude the influence of the thermo-contact electromotive force on the measurement results, the polarity change is provided in the device while changing within the forward and reverse.

The ECA pressing has accompanied by changing the shift direction to the opposite. Changing the deformation sign makes an influence on the structure formation. The main deformation axes undergo a rotation, and as the material passes through each subsequent pass, the axes rotation direction changes to the opposite during each pass. It contributes to the intensive fragmentation of structural components and isotropic structure formation at each deformation cycle [5]. Redistribution of the crystal lattice micro

distortions occurs between the individual micro volumes of the plastically deformed material at each subsequent deformation zone and cycle, as a result of appearance a large number of directions along which an elementary shift in the micro volumes of the deformed material may occur. It also provides the intensive process of crushing mosaic blocks and individual crystallites, as the result of which a fine-dispersed structure has observed with the formation of many defective boundaries [6]. The density, microhardness, structure, and electrical resistance of samples have measured and investigated after ECA pressing.

3. Research results

The sample density changing lengthwise, which allows determining dimensions of the deformation zone with UFG structure presented in Figure 1. Dimensions of the deformation zone at the initial porosity of 40% are much less than at the initial porosity of 10% despite the lower energy intensity of the operation. Therefore, we recommend using a billet with an initial porosity of 10-15 % for production of predetermined shape parts [7].

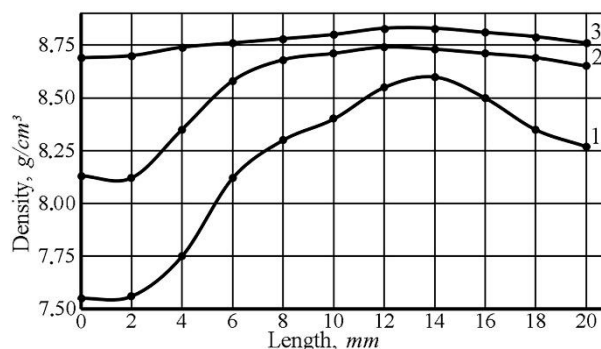


Fig. 1. Changing the density lengthwise the sample at initial porosity: 1 - 40 %, 2 - 20 %, 3 - 10 %.

A homogeneous microstructure has formed as the result of the ECA pressing in the intensive metal flow direction, the grains elongation and the fraction of high-angle grain boundaries are determined by the number of passes and the degree of deformation [8]. The most ordered, equigranular, and banded microstructure with low-angle boundaries has obtained in the test sample after the third pass [9]. The smallest grain size in the deformation zone was ~ 80 nm while increasing the distortion level of all grains.

Experiments have shown clearly that nanostructured zone in the sample increases while decreasing the initial porosity value [10].

The density increase, as well as the presence of ultrafine-grained structure, provided increasing the strength of the powder material. The microhardness changing after the third pass presented in Figure 3. As seen, the microhardness in the central zone of the sample is almost homogeneous, but it varies by the cross-section, which obviously provides an anisotropy of physical and mechanical properties [11].



Fig. 2. The microstructure of the deformation zone after the third pass, $\times 3000$

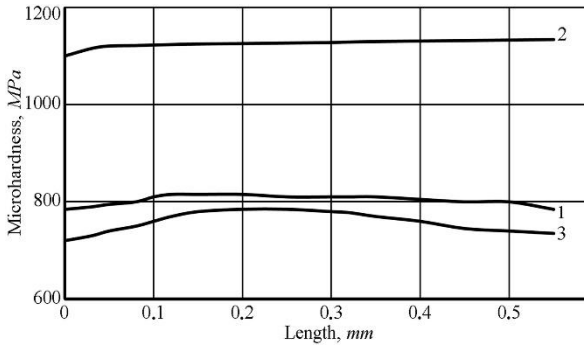


Fig. 3. The microhardness changing by the longitudinal section of the sample after the third pass: 1, 3 - are the upper and lower zones; 2 - is the central zone.

The direct current electrical resistance measuring results presented in Table 1.

Table 1

The direct current electrical resistance measuring results

Samples after ECA pressing	R, Ohm	R, Ohm, copper (tabulated value)
Longitudinal section	$2.8 \cdot 10^{-5}$	$1.72 \cdot 10^{-6}$
Cross-section	$4.9 \cdot 10^{-5}$	

A considerable variation in the electrical resistance measurements by the cross-section of the sample is explained by the formed elongated structure after the ECA pressing with the smaller number of grain boundaries in the longitudinal section than in the transverse section. The smaller number of grain boundaries and defects in the crystal lattice in the longitudinal direction corresponds to lower electrical resistance values.

4. Application of research results

Considerable reserves for increasing a speed of fuses in devices are in using of UFG powder copper for production of fuse links. Fuse links made of such material demonstrate a higher electrical resistance than the cast conductors and 15% lower heat capacity upon the average, which results in a much higher speed of fuses.

The fuse link is a plate with the thickness of 0.3 mm and cross-sectional dimensions of 0.5×0.5 mm. Such plates have obtained by electrical discharge sawing, which allowed preserve a UFG structure and high electrical resistance of samples.

The work of electric current $P(t, T)dt$ causes the fuse heating up from the temperature T to $T+dT$ while operating in short-circuit mode during the time interval from t to $t+dt$. Since the process is rapid, heat exchange with the environment may be neglected, and the following equality fulfilled:

$$P(t, T)dt = c(T)mdT, \quad (1)$$

where $P(t, T)$ - is the electric current power allocated in the volume of a fuse, W; $c(T)$ - is the specific heat of fuse material, J/(kg·K); m - is the weight of a fuse, kg.

Since the current power is:

$$P(t, T) = I^2(t)R(T), \quad (2)$$

where $I(t)$ - is the short-circuit current through the fuse, A; $R(T)$ - is the fuse resistance changing during its heating, Ohm, obtained:

$$I^2(t)dt = \frac{c(T)mdT}{R(T)}. \quad (3)$$

Since the fuse operating time mainly determined by its heating time from the operating temperature T_0 to the T_s melting temperature of the material from the fuse is made of, and also neglecting the time dependence of the short-circuit current, we obtain the following expression for evaluation of the trip time:

$$t_s = \frac{m}{I_s^2} \int_{T_0}^{T_s} \frac{c(T)dT}{R(T)} = \frac{d_0 l_0 S_0}{I_s^2} \int_{T_0}^{T_s} \frac{c(T)S(T)dT}{\rho(T)l(T)}, \quad (4)$$

where I_s - is the average value of short-circuit current, A; d_0 - is the fuse material density at the operating temperature T_0 , kg/m³; l_0 - is the fuse length at the operating temperature T_0 , m; S_0 - is the fuse cross-sectional area at the operating temperature T_0 , m²; $\rho(T)$ - is the resistance of the fuse material, which changes during its heating, Ohm·m; $S(T)$ - is the cross-sectional area of the fuse m²; $l(T)$ - is the fuse length, m.

Approximating dependences obtained by the experimental results for fuse links made of cast and UFG powder copper have used for verification of the proposed fuse trip time calculation technique.

The dependence of heat capacity on the temperature of cast copper, J/(kg·K):

$$c(T) = 259 + 0.363T - 1.3 \cdot 10^{-4}T^2. \quad (5)$$

The dependence of resistivity on the temperature of cast copper, Ohm·m:

$$\rho(T) = 9.78 \cdot 10^{-9} + 3.22 \cdot 10^{-11}T + 2.78 \cdot 10^{-14}T^2. \quad (6)$$

The dependence of density on the temperature of cast copper, kg/m³:

$$d_0(T) = 9.03 \cdot 10^3 - 3.15 \cdot 10^{-1}T - 4.25 \cdot 10^{-5}T^2. \quad (7)$$

The dependence of the linear expansion coefficient on the temperature of cast copper, 1/K:

$$\alpha(T) = 1.35 \cdot 10^{-5} + 7.7 \cdot 10^{-9}T - 2.1 \cdot 10^{-12}T^2. \quad (8)$$

The tested fuses from UFG powder copper are in good compliance with the theory, which takes into account the dependence of heat capacity, resistivity, density, geometric dimensions and other parameters of the fuse-link on its temperature.

The trip time simulation results for fuses made of UFG powder copper depending on the resistance, cross-sectional area and short-circuit current of samples presented in Fig. 4 - Fig. 6.

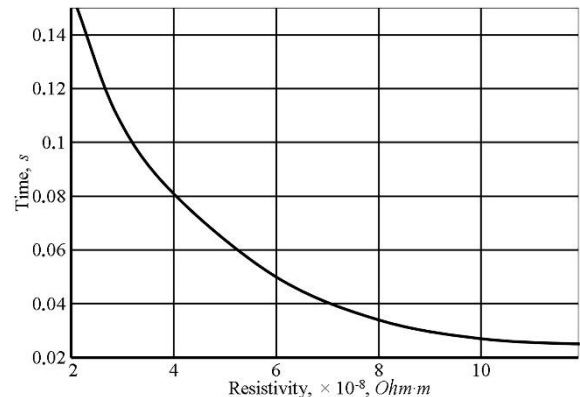


Fig. 4. The dependence of the fuse trip time on the electrical resistivity of UFG powder copper.

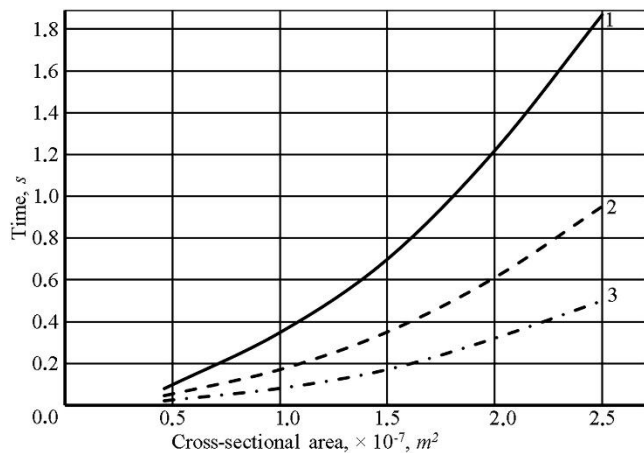


Fig. 5. Dependences of the fuse trip time on the cross-sectional area for different values of the resistance of the samples: 1 - is the cast copper, $\rho = 1.7 \cdot 10^{-8} \text{ Ohm}\cdot\text{m}$; 2 - is the UFG powder copper, longitudinal section, $\rho = 8.9 \cdot 10^{-8} \text{ Ohm}\cdot\text{m}$; 3 - is the UFG powder copper, cross-sectional area, $\rho = 17.5 \cdot 10^{-8} \text{ Ohm}\cdot\text{m}$.

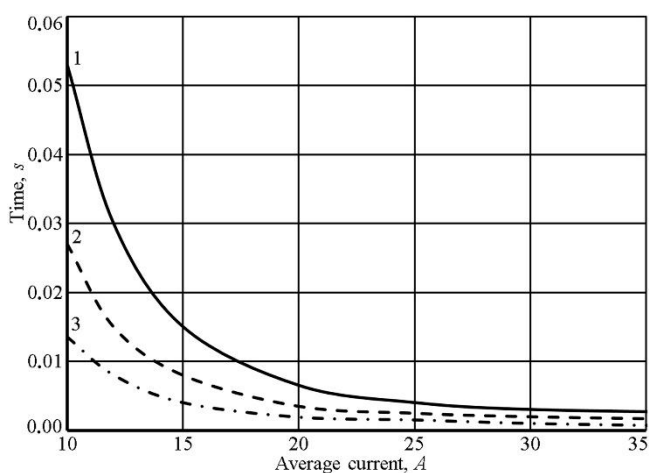


Fig. 6. Dependences of the fuse trip time on the average value of a short-circuit current for various resistivity values of samples: 1 - is the cast copper, $\rho = 1.7 \cdot 10^{-8} \text{ Ohm}\cdot\text{m}$; 2 - is the UFG powder copper, longitudinal section, $\rho = 8.9 \cdot 10^{-8} \text{ Ohm}\cdot\text{m}$; 3 - is the UFG powder copper, cross-sectional area, $\rho = 17.5 \cdot 10^{-8} \text{ Ohm}\cdot\text{m}$.

The UFG copper powder material has recommended for the fabrication of fuse links.

5. Conclusions

The problem of using the UFG powder material obtained by the ECA pressing from a copper powder for the production of fast-acting fuse links has been solved.

The dependences of density and microhardness of the sample under various deformation conditions have obtained lengthwise. A deformation zone of constant density is determined and recommended for using in the production of fuse links. The dependence of the electrical resistance along the sample cross-

section and across the deformation axis has determined. A fuse links calculation has proposed.

Implementation of the UFG copper powder material for the production of the links will ensure a significant increase in the speed of the fuse link at negligible electric power loss compared to the payload.

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PERSPECTIVE COMPOSITE MATERIALS FOR GENERAL AND SPECIAL MECHANICAL ENGINEERING

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Abstract: The work considers the use of carbon nanotubes to enhance the functional characteristics of polymer materials. The results on studies of the electrophysical properties of polymers doped with carbon nanotubes are presented and prospects for the use of such materials are discussed.

Keywords: ELECTROCONDUCTIVE POLYMER COMPOSITES, DOPING, CARBON NANOTUBES, MODIFICATION

1. Introduction

The production of new equipment, special-purpose constructions with a high functional properties requires the development of new materials or the improvement of traditionally used ones. An effective solution to these problems is based on the development of new composite materials doped by micro- and nanostructures. Carbon nanotubes (CNTs), which have a complex of unique physical-chemical properties, can be considered as one of the most promising types of modifiers [1]. Such CNT-based fillers make it possible to vary both the strength characteristics of polymers and in a wide range the electrical conductivity of the polymer matrix [2, 3]. This greatly expands the possible applications of composite materials. Due to their electronic properties and high aspect ratio (the ratio of length to diameter) of carbon nanotubes, their addition to the polymer matrix in an amount of 0.2% causes an increase in the electrical conductivity of the resulting composite by 8-10 orders of magnitude. In this case, the percolation nature of the conductivity of the material appears, according to which, with a small content of the conductive additive, charge transfer occurs through a small number of conducting channels formed upon the contact of the additive particles.

Despite of all the attractiveness of using carbon nanostructures to create promising composites, there is a number of problems that prevent their wide application. One of them is the problem of obtaining nanocomposites based on carbon nanotubes with their uniform distribution in the matrix and the need for the formation of covalent bonds between the surface of nanotubes and polymer. Without further modification, CNTs tend to form agglomerates. In addition, the graphene surface of a nanotube can form only weak van der Waals bonds with a polymer matrix, which inhibits the achievement of useful properties in polymer composite materials. In order to better disperse the modifier in the matrix, and also to form covalent bonds between the matrix and the nanoparticles, the functionalization of nanotubes is used [4, 5].

It should be noted that the final properties of the composite material doped with carbon nanotubes depend significantly on a number of factors. A key element in creating composites with given properties is a fundamental understanding of the mechanism of composites formation in the interaction of constituent components, basic and alloying. In the case of CNTs used as the doping component, the determining factor is their morphology, electronic structure, concentration, surface state, in particular, the presence of functional groups interacting with the matrix medium.

The purpose of this paper is to study the concentration dependence of electrical conductivity of a composite material based on ABS-plastic and functionalized carbon nanotubes.

2. Materials and Methods

As carbon nanotubes conical carbon nanotubes were used. Conical carbon nanotubes were grown by pyrolysis of granular polyethylene. These nanotubes are several microns in length, with outer diameters ranging between 40 and 50 nm and inner channels

varying between 9 and 20 nm. The fringe spacing is 0.34 nm. Such nanotubes are characterized by a large number of broken chemical bonds necessary for the attachment of external molecular groups.

An ABS-1035, produced by PJS company Kazanorgsintez (Kazan, Russia) was used as polymer matrix.

For the production of composite samples based on ABS doped by carbon nanotubes, a specially developed technique including thermochemical and ultrasonic treatment was used [6]. A series of ABS/CNTs composites with varied amounts of CNTs (0.125, 0.25, 0.5, 1 wt.%) were prepared.

The concentration dependence of electrical conductivity of a composite material based on ABS and functionalized carbon nanotubes was measured by using four-probe van der Pauw method at ambient temperature.

3. Results and Discussion

Figure 1 shows the samples of a polymeric composite material based on ABS and functionalized carbon nanotubes with different concentrations. The concentration dependence of electrical conductivity of ABS/CNTs composites is presented on Fig.2.

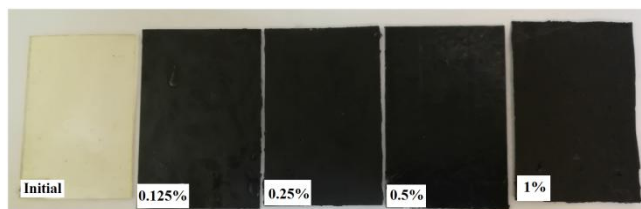


Fig.1 Samples of a polymeric composite material based on ABS and functionalized carbon nanotubes with different concentrations.

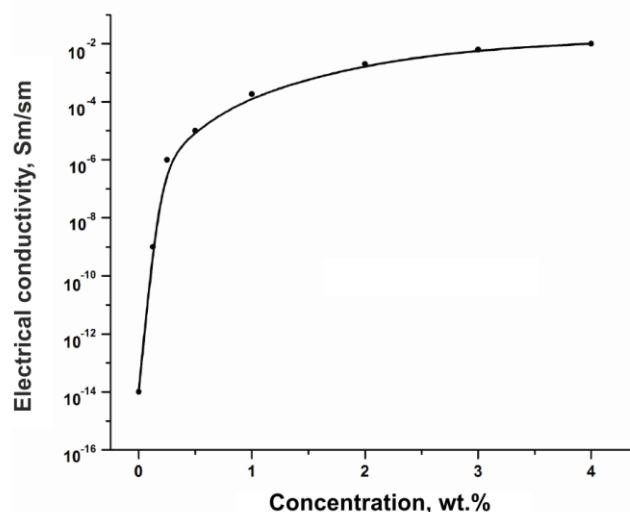


Fig.2 Concentration dependence of electrical conductivity of ABS/CNTs composites.

It can be seen from Fig. 2 that the increase in the electrical conductivity is nonmonotonic: its sharpest change was observed in a narrow range of filler concentrations, which allows to consider a dielectric-metal transition or a percolation transition when the amount of the conducting particles in a material equals to the percolation threshold.

Thus, in this paper the manufacturing of a composite material with controlled electrical conductivity based on ABS and carbon nanotubes is shown. The developed electrically conductive composite material based on polymers and CNTs can be used, for example, in the manufacturing of conductive pastes and adhesives, as electrically conductive liners and plates in modern composite machine parts in general and special engineering.

4. Acknowledgements

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THE COMPRESSION NATURE OF THE „WURTZITE BORON NITRIDE-DIAMOND” SINTERED UNDER HIGH PRESSURE

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Abstract: The results of experimental studies of the compression process during the sintering under high pressure conditions of wurtzite boron nitride and diamond powders mixture of submicron sizes obtained by different technologies are given.

It is determined that the compaction level at obtaining compositions depends on the dispersion and nature of the diamond component.

Interaction of wurtzite boron nitride with diamond proceeds more intensively with diamonds of dynamic synthesis, but it is accompanied by their partial graphitization.

KEY WORDS: WURTZITE BORON NITRIDE, DIAMOND, DISPERSION, SINTERING, DENSITY.

Introduction.

A considerable amount of work is devoted to obtaining composite polycrystalline materials on the basis of superhard phases of boron and carbon nitride. In experiments [1-4] mixtures of boron and carbon nitride were used, in which one of the components was used in the state of thermodynamic stability under high pressure conditions.

However, the production of composites from such mixtures requires very high barometric parameters for sintering and direct phase transformations in dense modifications of components with a layered crystalline lattice, therefore, in [1], when composite from a mixture of hexagonal boron nitride and diamond was obtained, to decrease barothermal parameters, catalytic impurities were used.

In addition, a number of papers [3-5] reported the obtaining of "CBN-diamond" composite materials when graphite-like boron carbonitride powders [3, 4], a mixture of diamond and graphite-like boron nitride [5] or diamond and sphalerite boron nitride [6, 7] were used.

In view of the fact that any data on the nature of the compression of said powder systems under the influence of high pressures and temperatures, there are no studies in this direction that are of scientific interest.

The purpose of the research is to study the peculiarities of formation in conditions of high static pressures and temperatures of polycrystalline composite materials in the system "wurtzite boron nitride - diamond".

Methods of experimental research. As the main component of a powder system mixture for the composite material production, the wurtzite boron nitride powder, which meets the requirements of TUU 75-12006.7-98, was used.

The main fraction of particles had a size in the developed plane of 0.1 ... 5 microns. According to electron microscopic studies, the powders were fragmented at two levels: the size of the first-level fragments was 0.5 ... 1.0 μm , and the second level was 50 ... 100 nm or less.

Diamond powders of different dispersion and origin were used as the second component of the mixture to produce the composite material - a catalytic synthesis of submicron sizes of 0.1/0 μm and dynamic nanosized range 0.005 ... 0.012 μm .

To study the compression kinetics and contact interaction between the system components, wurtzite boron nitride and diamond at sintering under high pressure, a mixture of their powders was prepared in a quantitative weight ratio of 90:10, from which pressed samples of a cylindrical shape.

The obtained samples in the high-pressure apparatus of the "toroid" type were subjected to high pressure $p = 7.7$ GPa and temperatures $T = 1500 \dots 1800$ °C at an interval of 100 °C for 5, 15, 30, 60 and 120 seconds.

The temperature control was carried out in accordance with the schedule of thermocouples previously obtained in the coordinates "power of heating – temperature".

At the beginning of the sintering process, the instant of heating was taken - non-isothermal conditions prior to the establishment of a quasi-stationary thermal regime.

The density of the sintered samples was determined by hydrostatic weighting method using the WLR-200 analytical scales with a maximum weighing range of 200 g and an accuracy of ± 0.15 mg.

Discussion of research results.

An analysis of the density measurements of sintered samples of the "wurtzite boron nitride-diamond" system composite material suggests the following.

According to studies of the compression nature of the initial mixture during the sintering of composite materials, it is observed its dependence on the origin and dispersion of the diamond component.

Despite the fact that the samples density from mixtures of boron nitride and diamonds of different origin in the initial state before the temperature action had approximately the same value, the compression nature of compositions is significantly different.

The samples density containing diamonds of static synthesis of 1/0 μm at the initial stage of sintering under nonisothermal conditions already after 3 ... 5 s significantly exceeds the characteristics of the composition with diamonds of explosive synthesis ($\rho_{st} = 2.68 \dots 2.84$ g/cm³ against $\rho_{dyn} = 2, 16 \dots 2.31$ g/cm³).

In the whole range of temperatures at all stages of sintering over $\tau = 60$ s, a gradual increase in sample density to a maximum value of $\rho = 3.412$ g/cm³ is observed.

Figure 1 shows the compression kinetics of the powder composition "wurtzite boron nitride - diamond" at sintering under high pressure conditions.

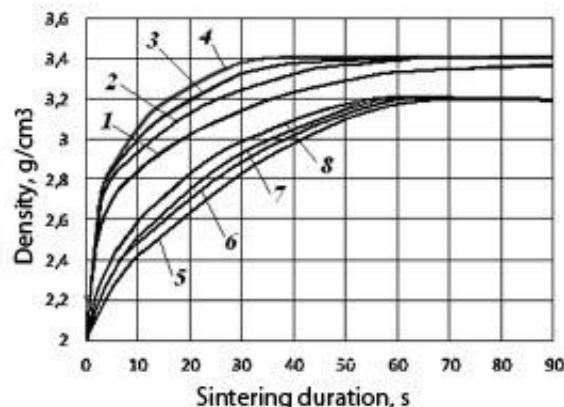


Figure 1. Compression kinetics of a powder composition, at sintering under high pressure conditions ($p = 8$ GPa): BN_w + static synthesis diamonds at $T = 1500^\circ\text{C}$ (1); $T = 1600^\circ\text{C}$ (2); $T = 1700^\circ\text{C}$ (3); $T = 1800^\circ\text{C}$ (4) and BN_w + dynamic synthesis diamonds at $T = 1500^\circ\text{C}$ (5); $T = 1600^\circ\text{C}$ (6); $T = 1700^\circ\text{C}$ (7); $T = 1800^\circ\text{C}$ (8).

The maximum density of the sintered composition " BN_w - Explosive Synthesis Diamond" was $\rho = 3.256$ g/cm³, and the nature of its change, depending on the sintering duration, is similar to

composition with static synthesis diamonds, but the sample density at all stages of sintering is significantly lower.

This is due to the fact that already at $T = 1000^\circ\text{C}$ there is a graphitization of dynamic synthesis diamonds [8] and, according to the data of X-ray analysis [9], at $T = 1600^\circ\text{C}$ the main part ($\sim 70\%$) is completely graphitized, while the other ($\sim 30\%$) forms a solid solution with boron nitride during the phase transformation of the wurtzite modification of BN into sphalerite [10].

It is the porosity that occurred as a result of the phase transformation of diamonds into graphite, which determines the characteristics of the sintered composition samples with the indicated density indices, and its volume corresponds to the mass fraction of diamonds that have been graphitized.

It was shown in [11] that at sintering diamond powders with particle sizes smaller than $0.3\ \mu\text{m}$ already at a temperature $T = 1600^\circ\text{C}$, as a result of their graphitization, the amount of counterweight in the pores of the samples is comparable to the value of the external pressure ($p = 8\ \text{GPa}$).

Accordingly, the results of our X-ray diffraction analysis of the matrix component of the composite based on wurtzite boron nitride are obtained.

The level of phase transformation $\text{BN}_w \rightarrow \text{BN}_{sf}$ in the composition of the explosive synthesis diamond under the same barothermic conditions, lower than the compositions based on static synthesis diamonds, due to pressure drop in the pores of the graphite, which is applied to the total pressure in the volume of samples and contributes to the intensification of the phase transformation of $\text{BN}_w \rightarrow \text{BN}_g$ in the case of discrepancy in the volume of samples of the thermodynamic stability conditions of high pressure nitride boron phases.

It is significant that for both systems of composition the maximum density of sintered samples is achieved at the temperature $T = 1700^\circ\text{C}$.

Such temperature of sintering superhard materials based on wurtzite nitride boron type composite-10 have the highest physical and mechanical characteristics, and in the given composition the main component is wurtzite boron nitride, which determines the nature of its formation.

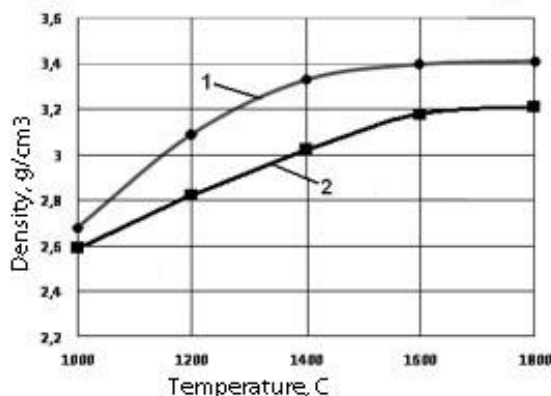


Figure 2. Compression characteristics of powder composition "wurtzite boron nitride - diamond" at sintering under high pressure conditions ($p = 8\ \text{GPa}$):

BN_w + static synthesis diamond $0,1/0\ \mu\text{m}$ (1);
 BN_w + dynamic synthesis diamond (2).

The increase of the sintering temperature of the composition to $T = 1800^\circ\text{C}$ and the duration of sintering up to 120s for both systems leads to a decrease in the material density, due to the peculiarities of the structure evolution of the polycrystalline material on the basis of BN_w during the sintering process, when the polycrystal dissolution occurs due to the development of plastic deformation by creep, which is associated with the formation of microstructure sections of the material on the monophase grains BN_{sf} basis with well-formed boundaries between them [12].

The compression process of the powder body is fully controlled by the development of plastic deformation, which mechanisms change in accordance with the evolution of the structural and phase state in the system of particles.

The fast packing compression state (initial stage) of sample is determined by the cooperative plasticity, which determines by the anisotropy of the lattice of wurtzite boron nitride and the insignificant energy of the basic packaging defects and the disordering of the initial BN_w due to the accumulation of basic defects in the packaging, which is accompanied by an increase in plasticity [13].

Cooperative deformation affects the formation nature of samples density, due to the next stage of structure formation - dissolution of the material.

Conclusion.

The results of the conducted studies indicate that the dispersion and nature of diamonds in the composition of the wurtzite boron nitride determine the characteristics of the polycrystalline material compression during the sintering under high pressure conditions. In the presence of static synthesis diamonds of submicron sizes, the compression process of the powder system during sintering corresponds to the general laws for wurtzite boron nitride in its pure form.

For composition with dynamic synthesis diamonds, the level of components compression of the composition is limited by partial graphitization, which is approximately 30% of the initial amount of the diamond component.

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INVESTIGATION OF THE EFFECT OF PRODUCTION PARAMETERS ON POLYSTYRENE NANO FIBER FORMATION FOR 12 WT %, 14 WT % AND 16 WT %

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Abstract— Polystyrene (PS) is a versatile plastic used to produce a wide variety of consumer products. It is used as a hard, solid plastic, mostly as food packaging and laboratory products. When polystyrene is mixed with various colorants, additives or other plastic materials, it is used to make electronic parts, automobile parts, toys, pots and equipments and more. Polystyrene is a vinyl polymer. It is structurally a long hydrocarbon chain with a phenyl group attached to the carbon atom. Polystyrene is produced by free radical vinyl polymerization from monomer styrene. In this study, the effect of production parameters on the formation of PS nanofibers was investigated. For this purpose, solutions were prepared at various mixing ratios (12 wt %, 14 wt % and 16 wt %) consisting of PS + dimethylformamide (DMF). The nanofiber structure was determined from these solutions. Electrospin method was used in production of nanofibers.

KEYWORDS: ELECTROSPIN METHOD, NANO FIBER, POLYSTYRENE.

1.Introduction

Nanoscience and nanotechnology are the study and application of extremely small things and can be used across all the other science fields, such as chemistry, biology, physics, materials science, and engineering. The ideas and concepts behind Nanoscience and nanotechnology started with a talk entitled “There’s Plenty of Room at the Bottom” by physicist Richard Feynman at an American Physical Society meeting at the California Institute of Technology (CalTech) on December 29, 1959, long before the term nanotechnology was used. In his talk, Feynman described a process in which scientists would be able to manipulate and control individual atoms and molecules. Over a decade later, in his explorations of ultra precision machining, Professor Norio Taniguchi coined the term nanotechnology. It wasn't until 1981, with the development of the scanning microscope that could “see” individual atoms, that modern nanotechnology began [1]. Nanotechnology is also being applied to or developed for application to a variety of industrial and purification processes. Purification and environmental cleanup applications include the desalination of water, water filtration, waste water treatment, groundwater treatment. In industry, applications may include construction materials, military goods, and nano-machining of nano-wires, nano-rods, few layers of graphene, etc. Also, recently a new field arisen from the root of nanotechnology is called nanobiotechnology [2].

2.Nanofiber

Nanofibers are fibers with diameters in the nanometer range. Nanofibers can be generated from different polymers and hence have different physical properties and application potentials. Polymer chains are connected via covalent bonds. The diameters of nanofibers depend on the type of polymer used and the method of production. All polymer nanofibers are unique for their large surface area-to-volume ratio, high porosity, appreciable mechanical strength, and flexibility in functionalization compared to their microfiber counterparts [3]. There are 8 methods of producing nanofiber. These are presented below

- Drawing method
- Phase separation method
- Self attachment method
- Chemical vapor deposition method (CVD)
- Nano-mold method

- Melt spray method
- Laser evaporation method
- Electrospin method

In this study, electrospin method was used.

Fig.1. illustrates the broad domains of polymer nanofibers that are being actively researched on. About 50% of the papers are focused on the electrospinning process development and characterization of fibers. Others are focused on innovative use of polymer nanofibers for a variety of applications in medicine, biotechnology, and engineering [4].

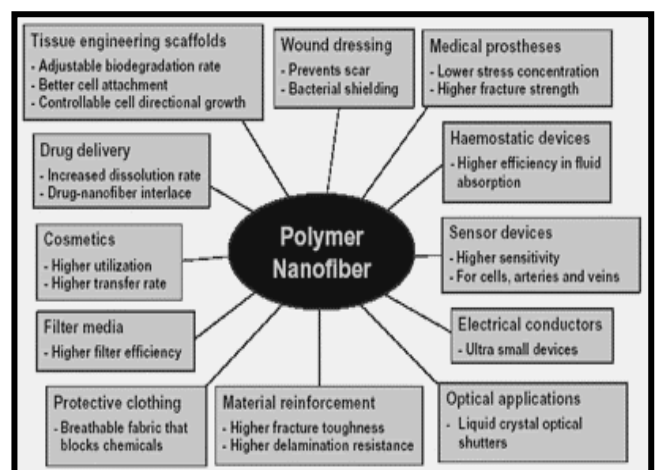


Fig. 1. Potential applications of polymer nanofibers. Polymer nanofibers are candidates for a number of applications in medicine, biotechnology, and engineering, because of their large surface area to volume ratio and unique nanometer scale architecture

3.Electrospinning theory and process

The schematic diagram of the electrospinning is illustrated in Fig.2 [5]. Electrospinning is a unique approach using electrostatic forces to produce fine fibers. Electrostatic precipitators and pesticide sprayers are some of the well known applications that work similarly to the electrospinning technique. Fiber production using electrostatic forces has invoked glare and attention due to its

potential to form fine fibers. Electrospun fibers have small pore size and high surface area. There is also evidence of sizable static charges in electrospun fibers that could be effectively handled to produce three dimensional structures. Polymer solution or the melt that has to be spun is forced through a syringe pump to form a pendant drop of the polymer at the tip of the capillary. High voltage potential is applied to the polymer solution inside the syringe through an immersed electrode, thereby inducing free charges into the polymer solution. These charged ions move in response to the applied electric field towards the electrode of opposite polarity, thereby transferring tensile forces to the polymer liquid. At the tip of the capillary, the pendant hemispherical polymer drop takes a cone like projection in the presence of an electric field. And, when the applied potential reaches a critical value required to overcome the surface tension of the liquid, a jet of liquid is ejected from the cone tip [6, 7].

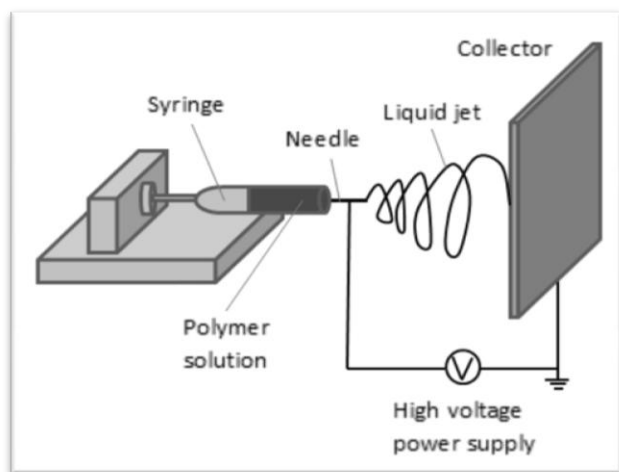


Fig. 2. The schematic diagram of the electrospinning experimental setup

It is essential to adjust electrospinning parameters to obtain uniform nanofibers. The parameters affecting the electrospinning process are represented in Fig. 3 [8].

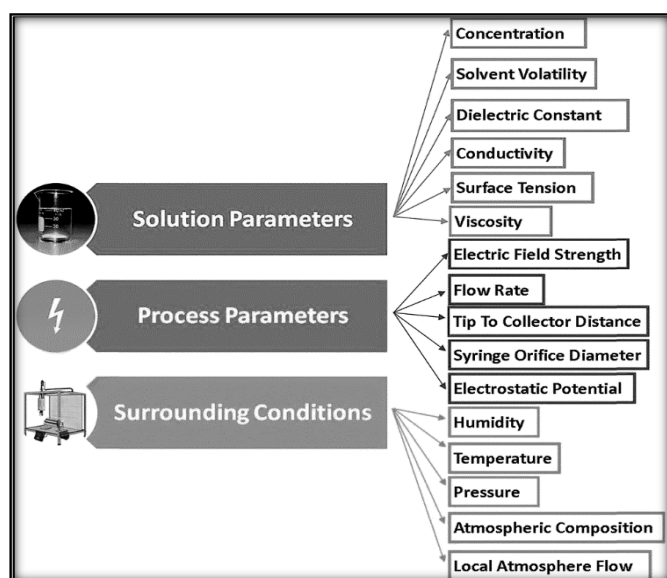


Fig. 3. Parameters affecting the electrospinning process

4. Experimental

In this study, PS and DMF were used. Polystyrene can be solid or foamed. General-purpose polystyrene is clear, hard, and rather brittle. It is an inexpensive resin per unit weight. It is a rather poor

barrier to oxygen and water vapor and has a relatively low melting point [9]. Polystyrene is one of the most widely used plastics, the scale of its production being several million tons per year [10]. Polystyrene can be naturally transparent, but can be colored with colorants. Uses include protective packaging (such as packing peanuts and CD and DVD cases), containers (such as "clamshells"), lids, bottles, trays, tumblers, disposable cutlery [9] and in the making of models. As a thermoplastic polymer, polystyrene is in a solid (glassy) state at room temperature but flows if heated above about 100 °C, its glass transition temperature. It becomes rigid again when cooled. This temperature behaviour is exploited for extrusion (as in Styrofoam) and also for molding and vacuum forming, since it can be cast into molds with fine detail. Polystyrene is slow to biodegrade and is therefore a focus of controversy among environmentalists. It is increasingly abundant as a form of litter in the outdoor environment, particularly along shores and waterways, especially in its foam form, and also in increasing quantities in the Pacific Ocean [11]. The molecular structure of PS is shown in Fig. 4.

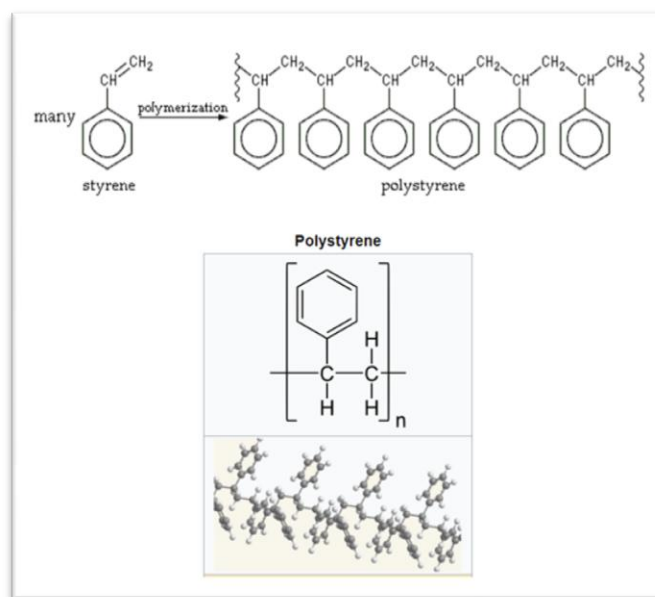


Fig.4. The molecular structure of PS [11]

N,N-Dimethylformamide is the commonly employed solvent for chemical reactions. DMF is a useful solvent employed for the isolation of chlorophyll from plant tissues. It is widely employed reagent in organic synthesis. It plays multiple roles in various reactions such as solvent, dehydrating agent, reducing agent as well as catalyst. It is a multipurpose building block for the synthesis of compounds containing O, -CO, -NMe₂, -CONMe₂, -Me, -CHO as functional groups. N,N-Dimethylformamide is a polar solvent commonly used in organic synthesis. It also acts as a multipurpose precursor for formulation, amination, aminocarbonylation, amidation and cyanation reactions [23]. The molecular structure of DM is shown in Fig. 5.

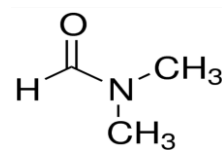


Fig.5. The molecular structure of DMF [12]

A PS with an average molecular weight (Mw) of 192000 g/mol and N, N-Dimethylformamide anhydrous, 99.8% were purchased from the Sigma Aldrich Co. all the materials were used as- received without further purification. The experimental setup is shown in

Fig.6. In this study, four types of solutions were prepared. These are 12 %, 14 %, 15 %, 16 % by weight. Then the mixture was stirred in a magnetic stirrer. Once the homogenization process ended, the solution samples were brought to the room temperature. After reaching the room temperature, the prepared electrospinning solutions were poured into a 2.5 mL syringes with 0.8 mm as inner diameter in order to proceed with the electrospinning setup.

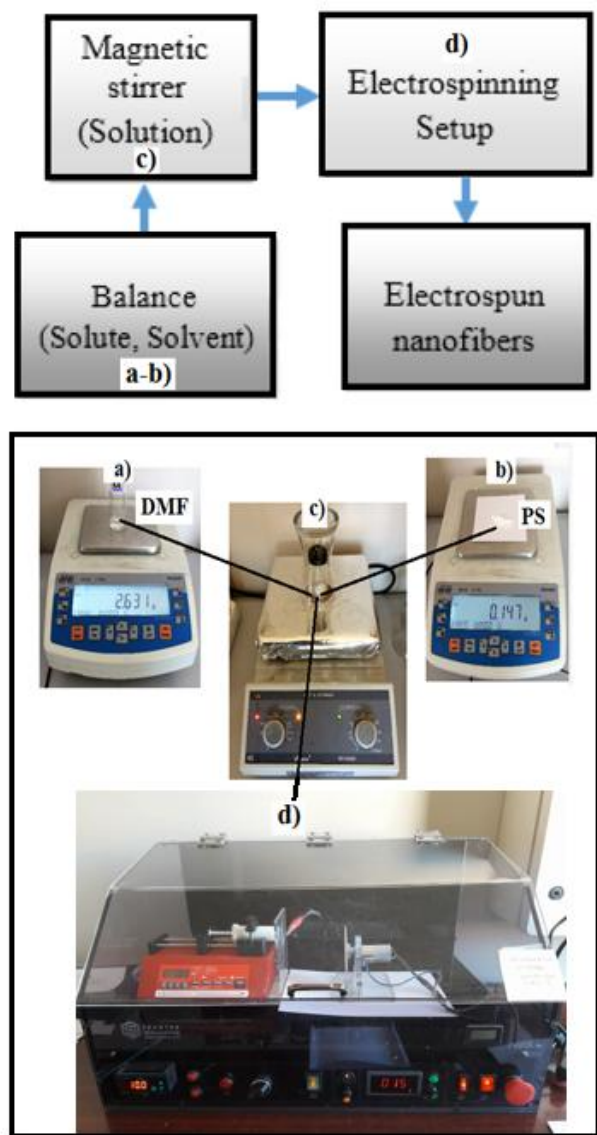


Fig.6. Experimental setup

Sample No : 1 (12 wt. % PS polymer content)

At 50 °C and 500 rpm, the solution was stirred for 1 hour.
 Applied voltage (kV) : 20
 The mass flow rate : 1 mL / h
 Distance between pipette and collector : 14 cm
 Collector Speed : 750 rpm (15%)
Result : The homogeneous surface did not occur (Fig.7)

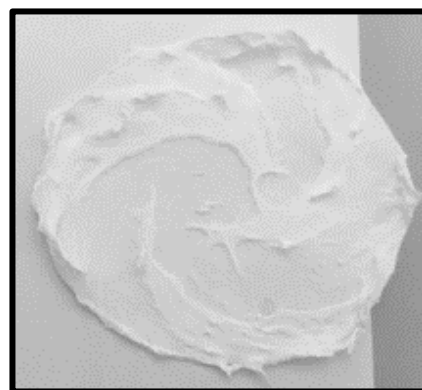


Fig. 7. Pictures of PS nanofibers for 12 wt. %

Sample No : 2 (14 wt. % PS polymer content)

At 50 °C and 500 rpm, the solution was stirred for 2 hour
 Applied voltage (kV) : 15
 The mass flow rate : 1 mL / h
 Distance between pipette and collector : 14 cm
 Collector Speed : 750 rpm (15%)
Result : The homogeneous surface did not occur. Also, in the middle part of the sample, a filamentous structure was observed (Fig. 8).



Fig. 8. Pictures of PS nanofibers for 14 wt. %

Sample No : 3 (15 wt. % PS polymer content)

At 90 °C and 500 rpm, the solution was stirred for 1 hour
 Applied voltage (kV) : 20
 The mass flow rate : 1 mL / h
 Distance between pipet and collector : 10 cm
 Collector Speed : 750 rpm (15%)
Result : The homogeneous surface did occur. But no nanofibers formed in the middle (Fig. 9).



Fig. 9. Pictures of PS nanofibers for 15 wt. %

Sample No :4 (16 wt. % PS polymer content)

At 90 °C and 500 rpm, the solution was stirred for 1 hour

Applied voltage (kV) : 20
The mass flow rate : 0.5 mL / h
Distance between pipette and collector : 16 cm
Collector Speed : 750 rpm (15%)

Result : The homogeneous surface occurred

The average diameter of nanofibers PS = 1591 nm (Fig.10).

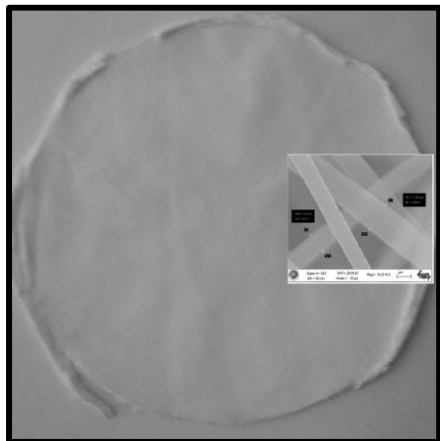


Fig. 10. Pictures of PS nanofibers for 15 wt. % and sample no : 4

Sample No : 5 (16 wt. % PS polymer content)

At 90 °C and 500 rpm, the solution was stirred for 1 hour

Applied voltage (kV) : 20
The mass flow rate : 1 mL / h
Distance between pipette and collector : 16 cm
Collector Speed : 750 rpm (15%)

Result : The homogeneous surface occurred

The average diameter of nanofibers PS = 1237 nm (Fig.11).

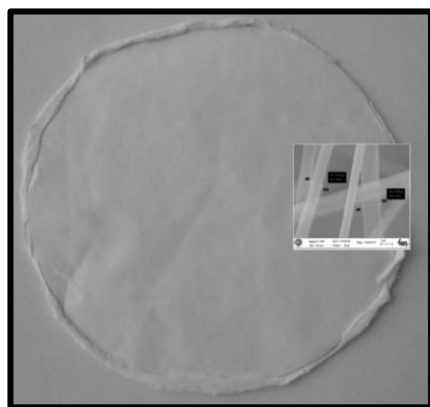


Fig. 11. Pictures of PS nanofibers for 15 wt. % and sample no : 5

Sample No : 6 (16 wt. % PS polymer content)

At 90 °C and 500 rpm, the solution was stirred for 1 hour

Applied voltage (kV) : 20
The mass flow rate : 1.5 mL / h
Distance between pipette and collector : 16 cm
Collector Speed : 750 rpm (15%)

Result : The homogeneous surface occurred

The average diameter of nanofibers PS = 1190 nm (Fig.12).

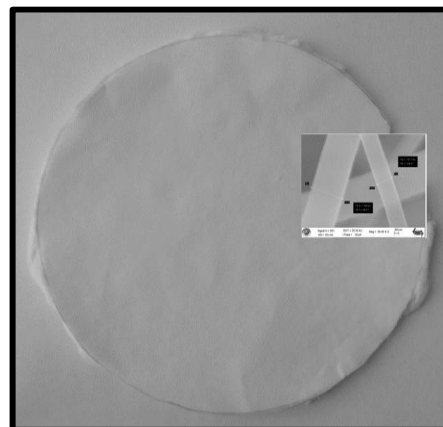


Fig. 12. Pictures of PS nanofibers for 15 wt. % and sample no : 6

5. Conclusions

In this study, the effect of production parameters on the formation of PS nanofibers was investigated. For this purpose, solutions were prepared at various mixing ratios (12 wt %, 14 wt %, 15 wt % and 16 wt %) consisting of PS+DMF. The nanofiber structure was determined from these solutions. Electrospin method was used in production of nanofibers. The homogeneous surface did not occurred for 12 wt %, 14 wt %, 15 wt % PS polymer content. At 16 wt % PS polymer content, the homogeneous surface occurred. At 16 wt % PS polymer content, it was determined that the average nanofiber diameter decreased as the mass flow rate increased.

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