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EVALUATION OF ENGINEERING SOLUTIONS IN WINE PRODUCTION

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Abstract: Contemporary wine production, unlike traditional one, requires investments in certain technological equipment necessary for the production process itself. In order to assess the justification of the production improvement in this area, the application of the engineering economy methods is very suitable. Methods for evaluation of financial efficiency and improvement of alternatives have been used in this paper. Specific solutions and recommendations have been obtained.

Keywords: TIME - MONEY, WINE PRODUCTION, ALTERNATIVES

1. Introduction

In the conditions of market economy, being competitive means to achieve an optimal relation between the price of a product and its quality. This, of course, applies to all branches of the economy, as well as to the wine production. To have a recognizable, quality wine with an enviable market share, inevitably implies constant improvement of the production technology, which must not be at the expense of the quality of future wine. In this paper, on the example of the winemaker which until now mainly relied on the traditional methods of wine production will be shown the justification of investment in the purchase of a discontinuous hydraulic press for pressing crushed grape (so called "kljuk"), in order for significantly higher quantity of quality wine to be obtained [1, 2].

2. Principles of Dependence Time – Money and Concept of Equivalence

Creating a larger or new value requires the engagement of capital in the form of money or assets. There is almost no engineering project that does not require capital investment in longer periods of time so that the time influence is an unavoidable factor that must be taken into account. Therefore, special attention should be given to the principles of time valuation of money that are essential for the evaluation of alternatives, while in this paper are used models given in Table 1.

Table 1: Models used to determine the time value of money.

Determination of F when P is known	$F = P(1+i)^N$	$F = P(F/P, i\%, N)$
Determination of P when F is known	$P = F / (1+i)^N = F(1+i)^{-N}$	$P = F(P/F, i\%, N)$
Determination of F when A is known	$F = A \left[\frac{(1+i)^N - 1}{i} \right]$	$F = A(F/A, i\%, N)$
Determination of P when A is known	$P = A \left[\frac{(1+i)^N - 1}{i(1+i)^N} \right]$	$P = A(P/A, i\%, N)$
Determination of A when F is known	$A = F \left[\frac{i}{(1+i)^N - 1} \right]$	$A = F(A/F, i\%, N)$
Determination of A when P is known	$A = P \left[\frac{i(1+i)^N}{(1+i)^N - 1} \right]$	$A = P(A/P, i\%, N)$

The basic elements of complex interest in tabulated models are:

- i – the effective interest rate, the amount which is paid per unit of money in units of time,
- N – number of interest periods, i.e. units of time during which interest is paid and which can be, day, week, month, 6 months or any agreed time interval,
- P – present value of money,

- F – future value of money,
- A – a complex amount, a sum of principal and interest that are paid in one uniform amount at the ends of the time (investment) periods.

Alternatives should be compared as much as possible when they give similar results, serve the same goal, or exercise the same function. It is only possible to do so by reducing them to an *equivalent basis* which depends on:

- interest rate,
- the amount of money involved,
- timing of cash income and / or expenses and
- the way in which the interest or profit for the capital invested is paid and the initial capital is returned.

3. Methods for the Evaluation of the Financial Efficiency of Investment Projects

One of the basic preconditions for applying the method for evaluating the financial efficiency of investment projects is to determine the Minimum Attractive Rate of Return (MARR) which is defined in the strategic goals of the management of the organization. In other words, this is the minimum acceptable rate of earnings under which a company or investor does not want to invest in a particular investment project, since it would be unprofitable. Therefore, the evaluation of the investment project is an analysis of the profitability, i.e. the applied inflow and outflow of cash, with a constant tendency to maximize the positive differences between the efficiency of the project and the investment.

There are a number of methods for evaluating investment projects, so it is difficult to single out one as the main one, since each one has its own advantages and disadvantages. However, depending on whether they take into account the time value of money, there can be distinguished:

- dynamic methods and
- static methods for evaluating the financial efficiency of investment projects.

Dynamic methods (take into account the time value of money) that are most frequently used in practice are:

The Present Worth Method (PW)

To find the PW as a function of $i\%$ (per interest period) of a series of cash inflows and outflows, it is necessary to discount future amounts to the present by using the interest rate over the appropriate study period (years, for example) in the following manner [5]:

$$PW(i\%) = \sum_{k=0}^N F_k(1+i)^k \quad (1)$$

Where are:

i - effective interest rate, or MARR, per compounding period.

k - index for each compounding period ($0 \leq k \leq N$).

F_k - future cash flow at the end of period k .

N - number of compounding periods in the planning horizon (i.e., study period).

The relationship given in Equation (1) is based on the assumption of a constant interest rate throughout the life of a particular project. If the interest rate is assumed to change, the PW must be computed in two or more steps [5, 6].

The Future Worth Method (FW)

The future worth method is based on the equivalent worth of all cash inflows and outflows at the end of the planning horizon (study period) at an interest rate that is generally the MARR. Also, the FW of a project is equivalent to its PW; that is, $FW = PW(F/P, i\%, N)$. If $FW \geq 0$ for project, it would be economically justified. Equation (2) summarizes the general calculations necessary to determine a project's future worth [5, 6]:

$$FW(i\%) = \sum_{k=0}^N F_k (1+i)^{N-k} \quad (2)$$

The Annual Worth Method (AW)

The Annual Worth (AW) of a project is an equal annual series of money amounts, for a stated study period, that is equivalent to the cash inflows and outflows at an interest rate that is generally the MARR. Hence, the AW of a project is annual equivalent revenues or savings (R) minus annual equivalent expenses (E), less its annual equivalent Capital Recovery (CR) amount. An annual equivalent value of R , E , and CR is computed for the study period, N , which is usually in years. In equation form the AW, which is a function of $i\%$, is [5, 6]:

$$AW(i\%) = R - E - CR(i\%) \quad (3)$$

Also, we need to notice that the AW of a project is equivalent to its PW and FW. That is: $AW = PW(A/P, i\%, N)$, and $AW = FW(A/F, i\%, N)$. Hence, it can be easily computed for a project from these equivalent values.

As long as the AW is greater than or equal to zero, the project is economically attractive. An AW of zero means that an annual return exactly equal to the MARR.

The Internal Rate of Return Method (IRR)

IRR method is the most widely used rate of return method for performing engineering analyses. It sometimes calls by several other names, such as investor's method. Discounted cash flow method, and profitability index.

By using a PW formulation, the IRR is the i' % at which:

$$\sum_{k=0}^N R_k (P/F, i'\%, k) = \sum_{k=0}^N E_k (P/F, i'\%, k) \quad (4)$$

Where are:

R_k - net revenues or savings for the k th year.

E_k - net expenditures including any investment costs for the k th year.

N - project life (or study period).

Once i' has been calculated, it is compared with the MARR to assess whether the alternative in question is acceptable. If $i' \geq \text{MARR}$, the alternative is acceptable; otherwise, it is not.

The External Rate of Return Method (ERR)

This method directly takes into account the interest rate (ϵ) external to a project at which net cash flows generated (or required) by the project over its life can be reinvested (or borrowed). If this external reinvestment rate, which is usually the firm's MARR, happens to equal the project's IRR, then the ERR method produces results identical to those of the IRR method.

In general, three steps are used in the calculating procedure. First, all net cash outflows are discounted to time 0 (the present) at $\epsilon\%$ per compounding period. Second, all net cash inflows are compounded to period N at $\epsilon\%$. Third, the external rate of return, which is the interest rate that establishes equivalence between the two quantities, is determined. The absolute value of the present equivalent worth of the net cash outflows at $\epsilon\%$ (first step) is used in this last step. In equation form, the ERR is the $i'\%$ at which

$$\sum_{k=0}^N E_k (P/F, \epsilon\%, k) (F/P, i'\%, N) = \sum_{k=0}^N R_k (F/P, \epsilon\%, N-k) \quad (5)$$

Where are:

R_k - excess of receipts over expenses in period k

E_k - excess of expenditures over receipts in period k

N - project life or number of periods for the study

ϵ - external reinvestment rate per period

Static methods (do not take into account the time value of money) are:

- method of the period of investment return,
- investment balance diagram.

4. Comparison Between Proposed Alternatives

Most of engineering problems usually have a limited number of possible solutions. Certainly, any of the proposed alternatives, as an input, implies different amounts of money for their realization, which results in different annual revenues and expenditures.

The inevitability of the existence of different factors, which are specific to each alternative, requires defining of a basis for comparison based on which their economic and financial evaluation will be done in the same time period.

When determining the observation period for the offered alternatives in relation to their total lifetime, two cases are possible:

1. Case: The lifetime is the same for all alternatives and equal to the observation period (Methods of equivalent value, Return Rate Methods).
2. Case: The lifetime is different for all alternatives and there are one or more alternatives whose lifetime is not equal to the observation period.

For the considered research, the 1st case is of interest where the justification of the investment will be tested on a concrete example of a winery, by using the method of equivalent value.

5. Application of A Method for the Evaluation of Alternatives in Wine Production

The analyzed winery has based its long-term business on the traditional way of grape processing, so that at present, it produces 20 000 liters of wine annually. The backbone of the production consists of "Žilavka" (white wine), "Vranac" (red wine) and Chardonnay wines, as well as several other types of grapevine varieties of the same name, such as Merlot, Cabernet Sauvignon, Procurator and various blends of these wines. Constantly taking into account the quality of the produced wine and in order to meet the needs of permanent but also new customers with sufficient quantities of wine, a need for production expansion occurred [3, 4, 7].

This, for sure, requires certain investments in terms of increasing the capacity and improving the technological process itself with the emphasis on keeping and possible increase of the achieved level of wine quality. The set goals are expected to be achieved by purchasing a discontinuous hydraulic press for pressing crushed grape (so called "kljuk"). This is a very important stage in the modern processing of red and especially white grapes. This, unlike the current gravity method of wicking out of wine, is expected to obtain a greater quantity of wine in a percentage of 10% compared to the same amount of processed grapes. The justification of this investment will be examined, firstly, through Research 1.

Research 1

The winery expects qualitative and quantitative business improvement through the purchase of a discontinuous hydraulic press which costs € 8000. Based on the experience gained in this field, they calculated that their annual income, by gaining larger amount of quality wines (2000 l), will be increased by 5000 €. Costs that are included in annual expenditures are:

- amortization according to Uniform (Straight – Line: SL) method 1000 €,
- costs of exploitation and labor force 200 €,
- loss of approximately 240 l of "komovica" schnapps 1200 €.

Data:

- investment (cost) 8000 €,
- lifetime 7 years,
- market value at the end of the lifetime 1000 €,
- annual income 5000 €,
- annual expenditure 2400 €.

It is necessary to determine the following:

- a) current, future and annual value when MARR = 12% for the year,
- b) internal rate of the project, whether it is acceptable?
- c) external rate of the project if we assume that $\varepsilon = 12\%$ for the year,
- d) simple and discounted return period.

Solution:

- a) $PW = -8000 \text{ €} + 2600 \text{ €} (P/A, 12\%, N) + 1000 \text{ €} (P/F, 12\%, N) = 4317, 48 \text{ €}$

$$FW = -8000 \text{ €} (F/P, 12\%, 7) + 2600 \text{ €} (F/A, 12\%, 7) + 1000 \text{ €} = 8545, 97 \text{ €}$$

$$AW = -8000 \text{ €} (A/P, 12\%, 7) + 2600 \text{ €} + 1000 \text{ €} (A/F, 12\%, 7) = 946, 17 \text{ €}$$

Since the values obtained for PW, FW and AW are greater than zero, the investment is justified.

b) to determine the internal rate of return (IRR) of the project, it is necessary to equalize the present value of the cash flow with zero:

$$PW = 0 = 8000 \text{ €} + 2600 \text{ €} (P/A, i\%, 7) + 1000 \text{ €} (P/F, i\%, 7);$$

Linear interpolation results in $i\%$ (IRR) = 27.18%.

As shown internal rate of return (IRR) is 27,18% and it is more than twice higher than minimum acceptable rate of return (MARR = 12%), so this project is quite safe from the perspective of risk.

- c) $FW = -8000 \text{ €} (F/P, i\%, N) = 2600 \text{ €} (F/A, 12\%, 7) + 1000 \text{ €}$

$$i\% = 19,12\%$$

Calculation by this method shows that the external rate of return is 19,12%, and since it is larger than the MARR of winery, the project is acceptable

d)

Table 2: Calculation for simple and discounted return period, MARR = 12% based on Research 1.

End of year (k)	Net cash flow	Accumulative PW under rate $i = 0\%/year$ over k years	PW of cash flow by the rate $= 12\%/year$	Accumulative PW under rate $i = 12\%/year$ over k years
0	- 8000	- 8000	- 8000	- 8000
1	2600	-5400	2321	-5679
2	2600	-2800	2073	-3606
3	2600	- 200	1851	-1755
4	2600	2400	1652	- 103
5	2600	5000	1475	1372
6	2600	7600	1317	2689
7	3600	11200	1628	4317

So, the economic justification for the purchase of a discontinuous hydraulic press is, from the standpoint of obtaining a higher quantity of quality wine, undoubtedly correct. However, the final decision on this investment should be made after analyzing all the accompanying factors. Namely, by obtaining a higher quantity of wine by pressing, a certain amount of "komovica" schnapps, which significantly contributes to the successful business of the winery, will be lost. Therefore, it is necessary from this aspect to compare these two alternatives through Research 2.

Research 2

Out of two offered options, one of which is innovation of the technological process of production (A), and the other for the traditional wine-producing method (B), it is necessary to choose a more acceptable solution. Between the offered solutions there is a difference between the capital invested and the income. The observation period is equal to the lifetime of the discontinuous hydraulic press and it is 7 years for both alternatives. The minimum acceptable wage rate is MARR = 12%.

Data:

Table 3: Comparations of Alternatives.

	Alternatives	
	A	B
Investment	8000 €	24000 €
Cost saving/year	2600 €	6000 €

Investment and cost savings are being approximated for Alternative B by which a larger quantity of wine in a percentage of 10% for settling newly emerging market needs wants to be received. Namely, by traditional production with the gravitational method of wicking out the wine (without pressing "kljuk"), it is possible to achieve, after the first streaming, wine yield up to 40%. This means that for the production of 2000 liters of wine, annually, quantity of 5000 kg of grapes is required. Taking into account the observed lifetime of the investment, the total required amount of grape is 35000 kg, which at current market prices is 22436 €. Proportional to the growth of the quantity of grapes for processing, needs for expansion of processing capacities grow, for which purpose, with the engagement of the labor force, it is necessary to invest 1564 €.

Cost savings of alternative B versus alternative A is higher on a basis of:

- absence of amortization costs in the amount of 1000 €,
- there are no costs of exploitation (electricity, maintenance ...) in the amount of 200 €,
- larger amount of "komovica" schnapps (450 l) in the amount of 2200 €.

Out of 100 kg of not pressed grape pomace about 15 l of “komovica” schnapps is obtained.

Solution:

Method of present value

$$PW(12\%)_A = -8000 \text{ €} + 2600 \text{ €} (P/A, 12\%, 7) = 3865, 13 \text{ €}$$

$$PW(12\%)_B = -24000 \text{ €} + 6000 \text{ €} (P/A, 12\%, 7) = 3381 \text{ €}$$

Method of annual value

$$AW(12\%)_A = -8000 \text{ €} (A/P, 12\%, 7) + 2600 \text{ €} = 847, 20 \text{ €}$$

$$AW(12\%)_B = -24000 \text{ €} (A/P, 12\%, 7) + 6000 \text{ €} = 741, 60 \text{ €}$$

Method of future value

$$FW(12\%)_A = -8000 \text{ €} (F/P, 12\%, 7) + 2600 \text{ €} (F/A, 12\%, 7) = 8545, 80 \text{ €}$$

$$FW(12\%)_B = -24000 \text{ €} (F/P, 12\%, 7) + 6000 \text{ €} (F/A, 12\%, 7) = 7477, 20 \text{ €}$$

Based on the results obtained from the calculation by all three methods, investment priority is on the side of the alternative A. In addition, the estimated market value of the discontinuous hydraulic press is 1000 € at the end of the lifetime, which, also supports the fact that innovation in the technological process is justified.

6. Conclusion

Parameters obtained by evaluating the offered alternatives in the case of the analyzed winery undoubtedly favor the alternative that includes innovation of the technological process. In Table 5. 1 it is noticeable that on the basis of a simple return period, investment costs are covered by revenues in the third year, and according to the discounted return period in the fourth year. The discounted return period shows a certain risk of investment, as the tendency is that in developed economic activities the return period should be no longer than 3 years. However, taking into account the seven-year lifetime of the investment and the fact that internal rate of return (IRR = 27, 18%) and the external rate of return (ϵ = 19, 12%) are significantly higher than the minimum acceptable rate of return of winery (MARR = 12%), with positive values of the method of equivalent value, the innovation of the technological process has no alternative.

Applying new or innovating existing technical and technological processes is an imperative relevant for all industries. However, improving productivity of production can be successful only in the case of quantity being followed by quality. In the conditions of market competition, only a quality product can provide a stable market position. To survive in this position is harder than to gain it, as it is often proved in practice. That's why the analyzed winery searches for a way to make its wine a combination of traditional and contemporary. The first step towards this is the introduction of a discontinuous hydraulic press into the technological process, by which can be determined the extent to which the grape pomace needs to be pressed, without adversely affecting the quality of the future wine. These presses, unlike the continuous ones, do not damage the hard parts of the grapes, which is also one of the prerequisites for quality wine. This will improve their business without the risk of endangering their participation in the sophisticated wine market.

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METHODS AND RESULTS OF EXPERIMENTAL RESEARCHES MACHINES FOR AUTOMATIC SORTING EGGS ON THE BASIS OF THE TECHNICAL VISION SYSTEM

МЕТОДИКА И РЕЗУЛЬТАТЫ ЭКСПЕРИМЕНТАЛЬНЫХ ИССЛЕДОВАНИЙ МАШИНЫ ДЛЯ АВТОМАТИЧЕСКОЙ СОРТИРОВКИ ЯИЦ НА БАЗЕ СИСТЕМЫ ТЕХНИЧЕСКОГО ЗРЕНИЯ

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Abstract: This article shows the method and results of experimental RESEARCHES of machines for egg sorting into categories based on size and form using a vision system. The principal difference of the considered machine for automatic sorting of eggs into categories from existing sorting machines is the division of eggs into categories by size and the separation of substandard eggs in the flow. Experimental verification showed that the machine provides the division of eggs in size into four categories and the separation of eggs of irregular shapes and sizes in the flow. The accuracy of separation of eggs into categories depending on the performance. With a productivity of up to two eggs per second, the accuracy of egg separation averages 94.8%. With a productivity of three eggs per second was 87.4%.

KEYWORDS: SYSTEM, ALGORITHM, CONTROL, PROGRAM, MACHINE, CONTROLLER, CAMERA, EGG, SORT, CODESY

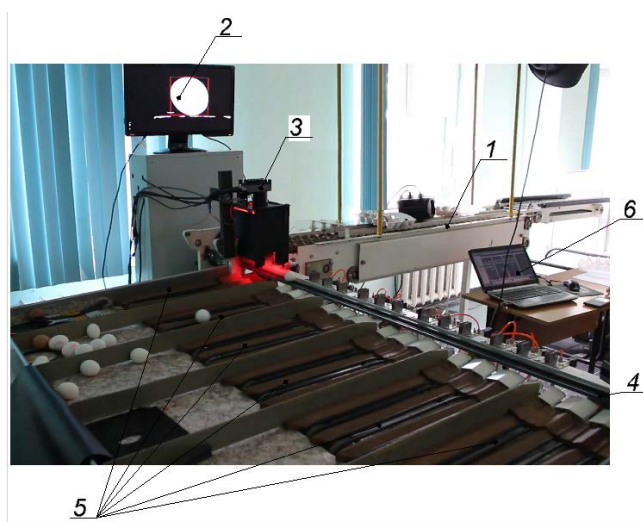
1. Введение

Целью исследований является экспериментальная проверка алгоритма и программы функционирования машины, а также технологические и технические параметры машины для автоматической сортировки яиц на базе системы технического зрения.

Машина для автоматической сортировки яиц с использованием системы технического зрения изготовлена на базе яйце сортировочной машины «РИТМ 8-3» и обеспечивает разделение яиц на четыре категории по размерам и отделение нестандартных по форме и размерам яиц. Принципиальным отличием новой машины для автоматической сортировки яиц от существующих аналогов заключается в разделении яиц на категории по размерам и отделения некондиционных яиц в потоке. Все технологические операции: подача яиц в зону контроля, получение и обработка изображения, классификация, разделения яиц на категории происходят в динамическом режиме, который обеспечивает возможность повышения производительности процесса сортировки не менее чем в два раза в сравнении с существующим методом разделения яиц на категории по массе. По значению площади продольного сечения изображения, яйца разделяются на категории по размерам (массе), а по значению коэффициента формы, который определяется как отношение квадрата периметра к площади продольного сечения изображения яйца, отделяют яйца, имеющие нестандартную форму. В макетном образце машины в качестве механизма перемещения яиц используется бесконечный транспортер с независимым частотно-регулируемым электроприводом, с обратной связью. Обратная связь реализована с помощью энкодера, который через контроллер дает возможность определения месторасположения каждого яйца на транспортере в движении. Энкодер установлен на вал редуктора электропривода. Вместо весовых механизмов установлены смарт камера и пневматические исполнительные клапаны, которые подключены к компрессору, рисунок 1.

Взаимодействие отдельных агрегатов машины осуществляется специально разработанной, оригинальной программой, в автоматическом и наладочном режимах [1].

Замена весовых механизмов на систему технического зрения, потенциально может обеспечить повышение производительности в три раза по сравнению с базовым вариантом. Система технического зрения разработана на базе смарт камеры NI-1772-EF00303A, которая обеспечивает определение геометрических параметров яиц (длина, ширина, площадь, периметр и коэффициент формы)



1- Роликово-ориентирующий транспортер, 2 - монитор с изображением анализируемого яйца, 3- Смарт камера с красной подсветкой, 4- ленточный, бесконечный транспортер, 5- секционный стол, 6- ноутбук.

Рисунок 1 – Общий вид машины для автоматической сортировки яиц с использованием системы технического зрения

Программы для обработки видеоизображения разработаны в среде «LabView» и «NI Vision Builder». Фотографирование яиц происходит в потоке, по команде оптического датчика «наличие яйца под камерой» [2]. Захват изображения производится программными средствами предоставляющие ряд алгоритмов. Используется следующая последовательность действий - поиск замкнутой фигуры методом проведения касательных к границам замкнутой поверхности. Далее полученные фигуры классифицируются по размеру площади изображения объекта. Если объект занимает площадь большую заранее predetermined значения считается, что этот объект яйцо. Для выделенного объекта (изображения проекции яйца), производим обработку изображения, определяем большой и малый диаметры, площадь, периметр в пикселях и значение коэффициента формы. Полученные данные передаются в контроллер. Для обработки информации о параметрах яиц, определение место расположения каждого яйца на транспортере и формирования команд на разделения яиц по категориям с помощью исполнительных механизмов используется контроллер с оригинальным программным обеспечением. Граничные значения признаков разделения яиц вводится с панели управления оператора.

2 Методика проведения исследований

Путем определения массы на электронных весах с точностью 0,1 гр. партия яиц, в соответствии с Европейским стандартом была разделена на четыре категории по массе: XL- яйца с массой выше 73 граммов (73-80), L - яйца с массой от 63 до 72 граммов, M - яйца с массой от 53 до 62 граммов, S- яйца с массой от 43 до 52 граммов. На стационарной автоматизированной установке определены значение коэффициента формы каждого яйца. К категории яиц несоответствующих требованиям стандарта были отнесены яйца с нестандартной формой и яйца с массой меньше 43 граммов и больше 80 граммов. К нестандартным по форме были отнесены яйца с коэффициентом формы меньше 13,0 и больше 15,0 в статическом режиме. Для определения граничных значений признаков разделения яиц на категории по размерам(массе) и отделения яиц нестандартной формы в динамическом режиме на макетном образце машины для автоматической сортировки яиц на базе системы технического зрения экспериментально определялись граничные значения площади сечения яиц каждой категории в пикселях и значения коэффициента формы. Граничные значения для категории яиц XL по размерам находятся в пределах: максимального значения, соответствующего массе 80 граммов и составит 73000 пикселей, минимальное значение соответствующее массе 73 граммов будет 65000 пикселей. Категории L от 60000 до 65000 пикселей, категории M от 52500 до 60000 пикселей и категории S от 45000 до 52500 пикселей. Значения коэффициента формы не зависит от размеров яиц, поэтому граничные значения коэффициента формы для всех категорий установлено в пределах: минимальное значение равное 13,0, а максимальное значение равное 15,0 [3]. Граничные значения признаков разделения яиц вводится в программу с панели управления оператора.

Экспериментальные исследования макетного образца машины для автоматической сортировки яиц на базе системы технического зрения, проводились в два этапа.

На первом этапе проведена экспертная оценка параметров яиц. Для этого яйца, с помощью электронных весов разделены на категории по массе согласно европейскому стандарту. Масса яйца измерялись на электронных весах марки DX-1200 с точностью до 0,1 грамма. На рисунке 2 показан момент определение массы яйца.



Рисунок 2 – Определение массы яиц на электронных весах марки DX-1200

После чего, штангенциркулем измерены диаметры классифицированных по массе яиц и определена форма каждого яйца. Яйца в каждой категории разделены на категории, кондиционные и бракованные по форме. Сортировка яиц проводилась в двух режимах. Первый режим при производительности два яйца в секунду. Скорость перемещение яиц устанавливался путем регулирования частоты на выходе частотного преобразователя. Для первого

режима частота на выходе преобразователя устанавливался равным 20 герцам.

Второй режим при производительности три яйца в секунду. Частота на выходе преобразователя устанавливался равным 30 герцам.

В каждом режиме для определения точности сортировки яиц машиной опыт проводился в трехкратной повторности.

В каждом эксперименте, для каждой категории яиц определена доля правильно отсортированных яиц из общего количества яиц данной категории (класса) [4,5].

$$T_{\text{класса}} = \frac{N_{\text{пр.класса}} + N_{\text{пр.брак}}}{N_{\text{я.класса}}} \quad (1)$$

Где:

Ткласса– точность класса

Нпр.класса– количество правильно определенных яиц в классе

Нпр.брак – количество правильно определенных яиц в браке

Ня.класса – общее количество яиц в классе

После чего, найдена средняя точность для всех категорий, по каждому эксперименту

$$Cp.T_{\text{класса}} = \frac{T_{\text{класса}}}{N_{\text{классов}}} \quad (2)$$

Где:

Ср.Ткласса – среднее значение точности класса

Ткласса– точность класса

Нклассов – количество классов, 5 классов

Перед началом эксперимента программа управления и исполнительные механизмы макетного образца машины настраивали, путем корректировки граничных значений разделение яиц на категории по площади и момента срабатывания электропневматических клапанов. На рисунке 3 показан фрагмент процесса наладки машины.

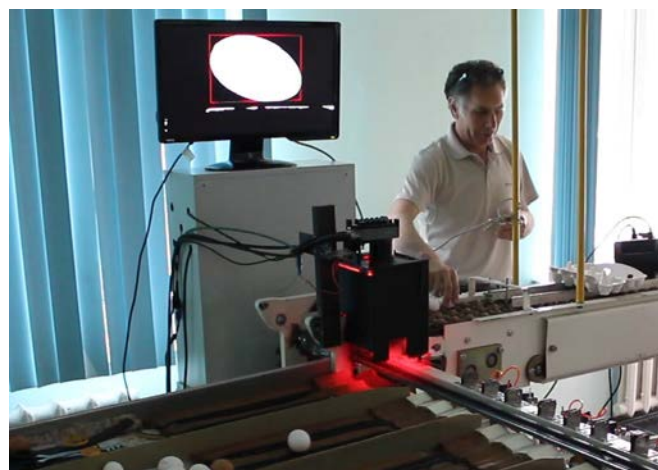


Рисунок 3 – Фрагмент процесса наладки машины.

Экспериментальные исследования проводились в двух режимах подачи яиц на сортировку, в режиме ручной подачи яиц на тросовый транспортер и в реальном режиме. Для каждого режима работы устанавливалось два значения производительности машины для автоматической сортировки, два яйца в секунду и три яйца в секунду. Максимальная производительность в реальном режиме работы ограничивается технологическими параметрами агрегатов яйце сортировочной машины «РИТМ 8-3» [6].

3 Результаты экспериментальных исследований

По результатам экспериментальных исследований на первом этапе установлено, что количество яиц категории

XL оказалась 8 штук; категории L – 31 штук; категории M – 31 штук; категории S – 26 штук. Яйца массой меньше 43 граммов – 12 штук, а массой больше 80 граммов – 12 штук. Количество яиц нестандартной формы из общего числа составило 16 штук. Процесс сортировки яиц в автоматическом режиме на макетном образце машины приведен на рисунке 4.



Рисунок 4 – Процесс сортировки яиц в автоматическом режиме
В таблице 1 представлены результаты сортировки яиц в режиме два яйца в секунду.

Таблица 1 – Результаты сортировки яиц в режиме два яйца в секунду

Класс	Экспертная оценка			Машинная сортировка						Битые	Точн. %
	Конд.	Брак	Итого	XL	L	M	S	Брак раз.	Брак форм		
XL	7	1	8	7	0	0	0	0	1	0	100
L	27	4	31	0	24	3	0	0	4	0	90
M	26	5	31	0	1	25	1	0	4	0	93,5
S	20	6	26	0	0	1	19	0	6	0	96,2
Брак раз.	24	0	24	1	0	0	1	22	0	0	91,6
Итого	104	16	120	8	25	29	21	22	15	0	94,2
Результаты сортировки яиц в режиме два яйца в секунду второй опыт											
XL	7	1	8	7	0	0	0	0	1	0	100
L	27	4	31	0	25	2	0	0	4	0	93,5
M	26	5	31	0	1	26	1	0	3	0	93,5
S	20	6	26	0	0	0	19	0	7	0	96,2
Брак	24	0	24	1	0	0	1	22	0	0	91,6
Итого	104	16	120	8	26	28	21	22	15	0	94,2

Результаты сортировки яиц в режиме два яйца в секунду третий опыт											
XL	7	1	8	7	0	0	0	0	1	0	100
L	27	4	31	1	24	2	0	0	4	0	90,3
M	26	5	31	0	0	27	1	0	3	0	94,7
S	20	6	26	0	0	0	19	0	7	0	96,2
Брак	24	0	24	0	0	0	1	23	0	0	95,8
Итого	104	16	120	8	24	29	21	23	15	0	95,4

В итоге точность сортировки по всем классам в первом эксперименте составила 94,26%, во втором 94,96% и в третьем 95,4%. Тогда среднее значение точность сортировки в трехкратной повторности составляет 94,8%. Аналогичные испытания проведены на режиме с производительностью три яйца в секунду. В таблице 2 представлены результаты сортировки яиц в режиме три яйца в секунду.

Таблица 2 – Результаты сортировки яиц в режиме три яйца в секунду первый опыт

Класс	Экспертная оценка			Машинная сортировка						Битые	Точн. сорт. %
	Конд.	Брак	Итого	XL	L	M	S	Брак раз.	Брак форм		
XL	7	1	8	6	0	0	0	0	0	2	75
L	27	4	31	0	24	2	0	0	5	0	90,3
M	26	5	31	0	0	25	2	0	4	0	94
S	20	6	26	0	0	1	18	0	6	1	92,3
Брак раз.	24	0	24	1	0	0	2	21	0	0	87,5
Итого	104	16	120	7	24	28	22	21	15	3	87,8
Результаты сортировки яиц в режиме три яйца в секунду второй опыт											
XL	6	0	6	6	0	0	0	0	0	0	100
L	27	4	31	0	22	3	0	0	5	1	83,6
M	26	5	31	0	1	22	3	0	5	0	87,1
S	19	6	25	0	0	3	16	0	5	0	84
Брак	24	0	24	2	0	0	2	20	0	0	83,3
Итого	102	15	117	8	23	29	21	20	15	1	87,6
Результаты сортировки яиц в режиме три яйца в секунду третий опыт											
XL	6	0	6	6	0	0	0	0	0	0	100

L	26	4	30	0	2	3	0	0	5	2	80
M	26	5	31	0	1	23	3	0	4	0	87,1
S	19	6	25	0	0	3	16	0	5	0	84
Бр к	24	0	24	2	0	0	2	20	0	0	83,3
Ит ог	101	15	11	8	2	29	21	20	14	2	86,8

На высоких скоростях яйцо неустойчиво ложится на бесконечный транспортер из-за чего увеличивается количество неправильно отсортированных яиц и яйца получают дополнительные механические повреждения.

Точность сортирования при производительности три яйца в секунду составила 87,4 %, дополнительные механические повреждения составили 5,2%.

4 Заключение

1. Оба электропривода машины устойчиво работают при регулировании частоты напряжения подающей на электродвигатели с выхода преобразователей в пределах от 20 до 50 герц. Регулирование скорости перемещения бесконечного транспортера обеспечивает возможность исследования, режимов работы системы технического зрения и системы разделения яиц на категории в широком диапазоне скорости от 0,065 м/с до 0,33 м/с, что обеспечивает регулирование производительности от одного до пяти яиц в секунду.

2. Проведенные экспериментальные исследования подтвердили работоспособность алгоритма и программы обработки информации о показателях качества яиц в потоке. Все агрегаты машины работают в соответствии с алгоритмом функционирования в режиме реального времени.

3. Машина для автоматической сортировки яиц на базе системы технического зрения обеспечивает разделение яиц по размерам на четыре категории и отделение яиц нестандартной формы и размеров в потоке. Точность разделения яиц на категории зависит от производительности. При производительности до двух яиц в секунду, точность разделения яиц составляет

в среднем 94,8%. Дополнительные механические повреждения яиц в процессе сортировки не превышает одного процента. При повышении производительности до трех яиц в секунду наблюдается сбой в работе механизма перекалывания яиц с транспортера ориентации на бесконечный транспортер и неустойчивое положение яиц на нем, что приводит к снижению точности сортировки и увеличению количества яиц с дополнительными механическими повреждениями. Точность сортирования при производительности три яйца в секунду составила 87,4 %, дополнительные механические повреждения составили 5,2%.

4. Для реализации потенциальных возможностей принципа разделения яиц на категории в потоке на базе системы технического зрения требуется модернизация механизма подачи яиц в зону контроля и усовершенствование транспортера перемещения и разделения яиц на категории в потоке.

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FINITE ELEMENT ANALYSIS OF STRESS OF VEHICLES FRICTION CLUTCH DIAPHRAGM

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Abstract: A friction clutch is mechanical assemblies built between the engine and transmission, that with friction transfers torque from the driving part to the driven (working) part (engine gearbox and other transmission). A diaphragm spring is one of the key component of a clutch assembly. A diaphragm spring is piece to high stress concentration in driving condition, this is often the cause of cracks and crashes spring. The stress of a diaphragm spring is analyzed by finite element method, measurement of stress and performed compare to stress obtained by expressions on Almen-Laszlo.

Keywords: CLUTCH FORCE, DIAPHRAGM SPRING, EXPRESSIONS OF ALMEN AND LASZLO, FRICTION CLUTCH

1. Introduction

By pressing on diaphragm spring, it creates the pressing force between driving disc, flywheel and pressure plate. With sufficient pressing force, a torque is transmitted from the flywheel to the transmission through the clutch. The centre portion of the diaphragm spring is slit into numerous fingers that act as release levers (unblock). When the clutch is disengagement the fingers are moved forward by the release bearing, it occurs separation of the driving disc and pressure plate from flywheel and thus prevents rotation of the driving disc.(Fig.1)

Diaphragm spring has not-linear characteristics between load (force) and deflection, compared to the helical compressed springs (hat a straight-line characteristic), this allows one compact assembly. The change to pressing force is in certain limits by wearing of the friction linings, at helical compressed springs force declines. Excluded force is smaller in comparison with helical compressed springs (Fig 2), [2], [5], [4]

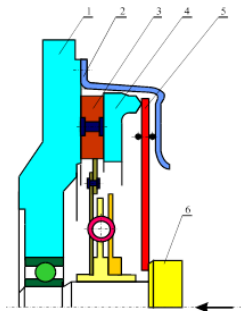


Fig.1. Clutch components :1.Flywheel 2.Clutch cover 3.Driving disc 4, Pressure plate 5. Diaphragm spring 6. Release bearing

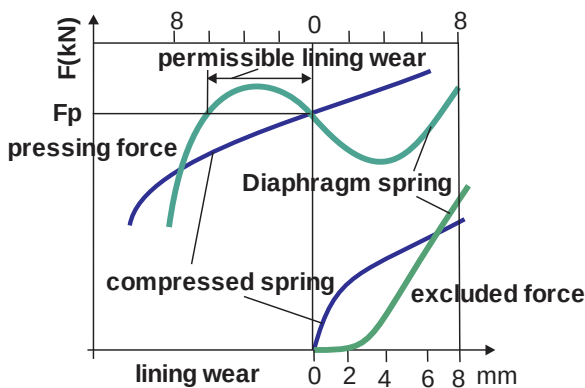


Fig.2. Pressing force and excluded force

Diaphragm spring is exposed to dynamic loads, increasing the number of changes the dynamic strength of the spring decreases. Dynamic strength of the spring is determined by Weller. Specimens are examined of the exactly same shape, size and quality. They undergo different variables loadings at break of the material. Thus obtained Weller curve from which can be determined dynamic strength.

The stress distribution across the radial width (tangential stresses) of the diaphragm spring is shown in Fig.3, [3].

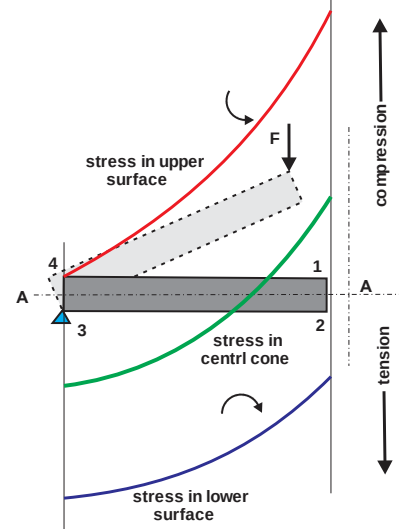


Fig.3. Stress-deflection

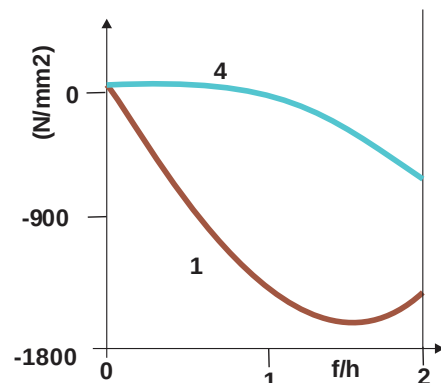


Fig. 3a. Stress-deflection/height of diaphragm spring. Curve 1 for the upper edge of the inner circumference. Curve 4 for the upper edge of the outer circumference.

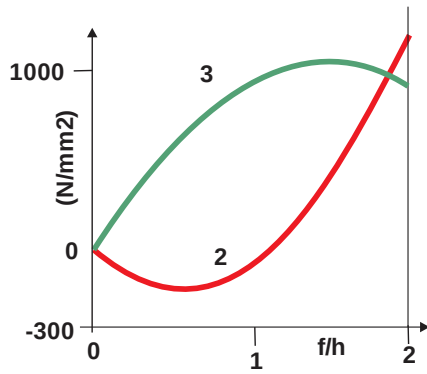


Fig. 3b. Stress-deflection/height of diaphragm spring. Curve 2 for the lower edge of the inner circumference. Curve 3 for the lower edge of the outer circumference.

2. Research

The purpose of this research is to calculate the stresses at static and dynamic loads on diaphragm spring. This calculation would have performed by expressions on ALMEN-LASZLO, calculation by finite element method and measurement of force and stress with suitable measuring equipment.

2.1 Calculation of force and stress with expressions of Almen and Laszlo's theory

Calculation of the stresses of the diaphragm spring were conducted with expressions of Almen and Laszlo's theory for calculation of diaphragm springs (Fig.4) [7], [6], [1]:

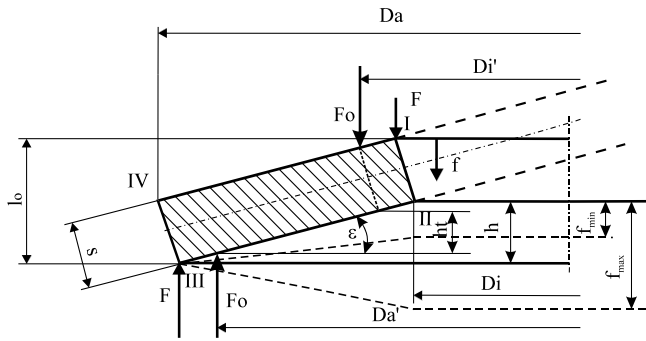


Fig.4. Forces of the spring

-Angle bending:

$$\varepsilon_1 = \varepsilon \frac{\pi}{180} \quad (\text{rad}) \quad (1)$$

where : ε - angle bending, degree, ε_1 -angle bending, radian

- Height of diaphragm spring:

$$h = \frac{D_a - D_i}{2} \tan \varepsilon \quad (\text{mm}) \quad (2)$$

where : D_a - outside diameter, D_i -inner diameter

-Relationship of diameters diaphragm spring:

$$\delta = D_a/D_i \quad (3)$$

- Coefficients α , k_1 , k_2 , k_3 are defined as follows :

$$\alpha = 4 \frac{E}{1 - \mu^2} \quad (4a)$$

$$k_1 = \frac{1}{\pi} \frac{\left(\frac{\delta - 1}{\delta} \right)^2}{\left(\frac{\delta + 1}{\delta - 1} \right) - \ln(\delta)} \quad (4b)$$

$$k_2 = \frac{1}{\pi} \cdot \frac{6}{\ln(\delta)} \cdot \frac{\delta - 1}{\ln(\delta)} - 1 \quad (4c)$$

$$k_3 = \frac{1}{\pi} \cdot \frac{6}{\ln(\delta)} \cdot \frac{\delta - 1}{2} \quad (4d)$$

$$k_4 = \frac{D_a - D_i}{D_{a1} - D_{i1}} \quad (4e)$$

$$p = \sqrt[2]{9 \cdot h^2 - 6(h^2 + s^2)} \quad (4f)$$

$$f_{\max} = (3h + p)/3 \quad (\text{mm}) \quad (4g)$$

$$f_{\min} = (3h - p)/3 \quad (\text{mm}) \quad (4j)$$

The variable in equation (4) are as follows:

α - Coefficient of elasticity of the spring material, N/mm²,
E-Module of elasticity, N/mm², μ - Poisson number of spring steel,
 D_{i1} -internal diameter of the diaphragm spring with supporting points, D_{a1} -outside diameter of the diaphragm spring with supporting points, f -deflection, $f_{\max}$ and $f_{\min}$ - deflection for extreme values of $F(f)$;

- Calculation of stress for the corresponding positions (N/mm²):

$$\sigma_{1,i} = \alpha \cdot \frac{s^2}{k_1 D_a^2} \cdot \frac{ff_i}{s} \left[-k_2 \left(\frac{h}{s} - \frac{ff_i}{2 \cdot s} \right) - k_3 \right] \quad (5.1)$$

$$\sigma_{2,i} = \alpha \cdot \frac{s^2}{k_1 \cdot D_a^2} \cdot \frac{ff_i}{s^2} \left[-k_2 \left(\frac{h}{s} - \frac{ff_i}{2 \cdot s} \right) + k_3 \right] \quad (5.2)$$

$$\sigma_{3,i} = \alpha \cdot \frac{s^2}{k_1 \cdot D_a^2} \cdot \frac{ff_i}{s} \cdot \frac{1}{\delta} \left[(2k_3 - k_2) \left(\frac{h}{s} - \frac{ff_i}{2 \cdot s} \right) + k_3 \right] \quad (5.3)$$

$$\sigma_{4,i} = \alpha \cdot \frac{s^2}{k_1 \cdot D_a^2} \cdot \frac{ff_i}{s} \cdot \frac{1}{\delta} \left[(2 \cdot k_3 - k_2) \cdot \left(\frac{h}{s} - \frac{ff_i}{2 \cdot s} \right) - k_3 \right] \quad (5.4)$$

where s - spring thickness.

-Pressure force on the diaphragm spring with supporting points is :

$$Ft(f) = \alpha \cdot k_4 \cdot \frac{s^4}{D_a^2 \cdot k_1} \cdot \frac{f}{s} \left[\left(\frac{h}{s} - \frac{f}{s} \right) \left(\frac{h}{s} - \frac{f}{2 \cdot s} \right) + 1 \right] \quad (6)$$

The diagram of change on pressing force of spring and spring with supporting points depending of deflection has been shown in Fig.5.

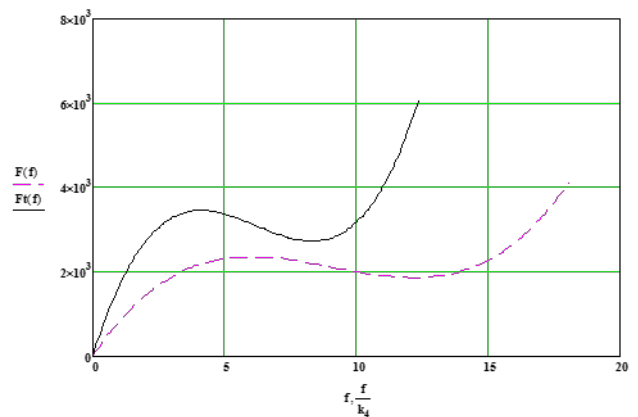


Fig.5. Diagram of the spring force (---) and the clutch force (—)
- Calculation of dynamic spring stress

Deflection at disengagement of clutch-control point f_{nis} is a sum of the height of diaphragm spring- h and the deflection from flat position on the spring to position disengagement of the clutch - δ_f
 $f_n = h + \delta_f$ (mm) (7)

where $\delta_f = \frac{Da - Di}{Da - d} \cdot l$ and l is path of clutch disengaging

- stress in point 3

-upper stress (OFF-deflection f_p) is :

$$\sigma_s = \alpha \cdot \frac{s^2}{k_1 \cdot Da^2} \cdot \frac{f_p}{s} \cdot \frac{1}{\delta} \left[(2 \cdot k_3 - k_2) \cdot \left(\frac{h}{s} - \frac{f_p}{2 \cdot s} \right) + k_3 \right] \quad (8)$$

Lower stress (stress in point 3 at deflection $f = h$)

$$-\sigma_d = \sigma_{3,2} \quad (9)$$

-Dynamic stress is :

$$\sigma_{dt} = \sigma_s - \frac{4}{7} \sigma_t \quad (10)$$

The calculation is performed on diaphragm spring for vehicles, from material (50CrV4-1.8159) and with next parameters:

$D_i = 313$ [mm]-internal diameter of diaphragm spring,
 $D_a = 395$ [mm]-outer diameter of diaphragm spring,
 $s = 5.21$ [mm]-spring thickness,
 $E = 206000$ [N/mm²]-Module of elasticity of the steel
 $\mu = 0,3$ -Poisson number of spring steel,
 $D_{i1} = 336$ [mm]-internal diameter of the diaphragm spring with supporting points
 $D_{a1} = 392$ [mm]-outer diameter of the diaphragm spring with supporting points,
 $\ell = 12$ [mm]-path of clutch disengaging,
 $d = 120$ [mm] released bearing diameter,
 $k_z = 0,95$ - efficiency coefficient.

The static stress is largest in point 1 and dynamic stress is largest in point 2 or 3, where plastic deformations of material occurs. In which point will has greater stress, it will depend on the ratio D_a/D_i and $h_0/s \geq 1.4$.

The results are given in the Table 1, 2 and 3.

Table 1: Pressing force and stress on the spring

	Ffi (mm)	FFi (N)	$\sigma_{1,i}$ (N/mm ²)	$\sigma_{2,i}$ (N/mm ²)	$\sigma_{3,i}$ (N/mm ²)	$\sigma_{4,i}$ (N/mm ²)
$f = f_{max}$	12,16	18590	-1736	497	1415	-354
$f = h$	9,01	21070	-1534	135	1260	- 62
$f = f_{min}$	-6,02	23550	-1172	-67,4	968	93

Table 2 : Pressure force on spring support

$f_{t \min} = f_{\min}/k_4$	4.109	$F_{t \max} = F(f_{\min})k_4$	34477
$f_{th} = h/k_4$	6.207	$F_{th} = F(h)k_4$	30846
$f_{t \max} = f_{\max}/k_4$	8.306	$F_{t \min} = F(f_{\max})k_4$	27215
mm	N		

Table 3: Dynamic stress

point	2	3
Upper stress	571,8	1428
Lower stress	137,8	1260,6
Dynamic stress	449,8	707,7
Durability dynamic strength	770 N/mm ²	

2.2 Estimate on stresses of the diaphragm spring with Finite Element Method (FEM)

In the used software package are included: drawing from the spring, dimensions, material, heat treatment (hardness) in the past two days of work the software package. A calculation is made with FEM, with 123845 nodes, the system gives the results of the change in stress from deflection[5].

Table 4 gives the results on the change on the stress dependence from deflection with finite elements.

Table 4: Results from calculated stress with FEM

f (mm)	2,72	5,44	8,16	9,1	10,9	12,6	13,6
σ (N/mm ²)	375	740	1020	1055	1140	1140	850



Fig. 6. Network of spring calculation. The network of the spring is divided into 21 parts and for each part is measured the stress on the underside of the spring.

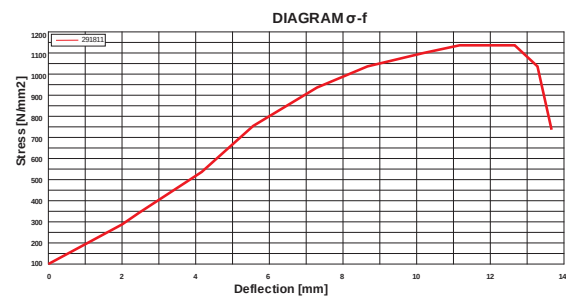


Fig.7. Stress change depending on the deflection, calculated by KE for Ø275

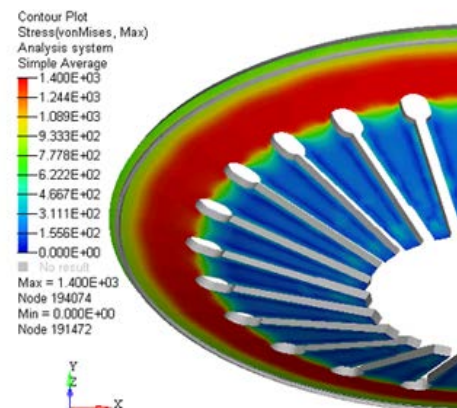


Fig.8a. The stress distributing of the lower surface of the spring

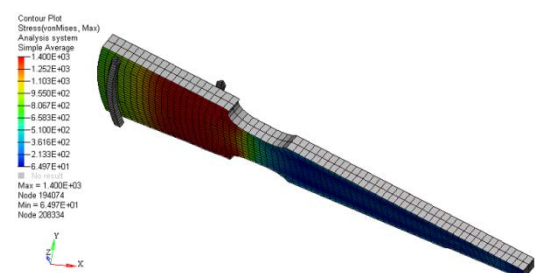


Fig.8b. The tangential stress of the lower surface of the finger

2.3 Estimate on stresses of the diaphragm spring with experimental measurement

Measurement of the force is made on the exam table (Fig.9) and with adding to the measured system is measured stress on the diaphragm spring (Fig.10a and 10b)

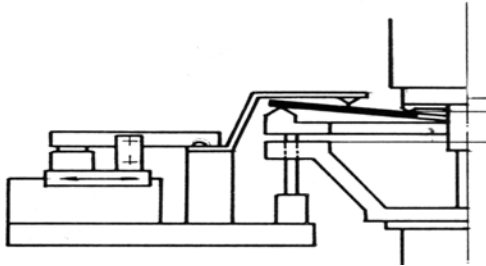


Fig.9. Diaphragm spring in disengagement position of the spring

Measuring tapes are mounted on spring 6mm of outer and inner diameter, ie Ø383mm (measured tangential stress) and Ø325mm.



Fig.10a. Diaphragm spring with measuring tapes



Fig.10b. Diaphragm spring with measuring tapes and test table

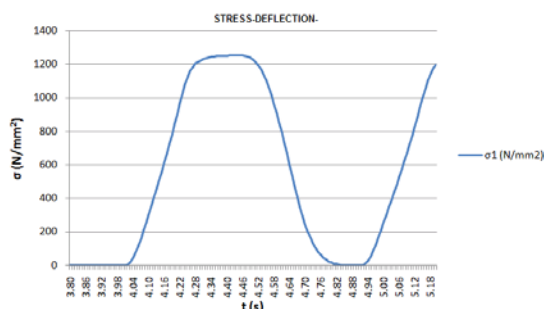


Fig.11. Diagram stress - time

Changing on measurement stress in a period of time is the ordinate and the time is the abscissa of the diagram.

Table 5: Value of stress. $\sigma_{3cal, 375AL}$ -stress calculated using expressions of Almen Laszlo' theory, $\sigma_{3est, 375FEM}$ -stress estimated with Finite Element Method, $\sigma_{3meas, 375EXP}$ -stress estimated with experimental measurement. All tree values for the stress are expressed in N/mm²

t(s)	4,17	4,27	4,37	4,47	4,52	4,57
$f_{(395)} \text{ mm}$	2,72	5,44	8,16	10,9	12,6	13,6
$f_{(375)} \text{ mm}$	2,06	4,12	6,16	8,23	9,53	10,3
$\sigma_{3cal, 375 AL}$	319	719	984	1191	1290	1336
$\sigma_{3est, 375 FEM}$	375	740	1020	1140	1140	850
$\sigma_{3meas, 375EXP}$	356	903	1231	1252	1253	1211

Table 6 deflection the calculated in relative to the measured stresses

$F_i \text{ (mm)}$	2,72	5,44	8,16	9,1	10,9	12,6	13,6
R_i	1,09	0,79	0,80	0,85	0,95	1,03	1,1
R_k	1,04	0,82	0,83	0,88	0,91	0,91	0,70

From the results shown in the table can be determined deviations from the calculated stresses in relation to the measured stresses:

$$R_i = \frac{\sigma_{3cal, 375AL}}{\sigma_{3meas, 375EXP}} = \frac{1065}{1243} = 0,85$$

$$R_k = \frac{\sigma_{3est, 375, FEM}}{\sigma_{3meas, 375, EXP}} = \frac{1085}{1243,5} = 0,88$$

3. Analysis of resultants and conclusions

From the deviations shown in the table can be concluded: there is deflection. Important is at higher loadings, and that's when the clutch is mounted in the vehicle (the spring is in a flat position - deflection 9,1mm) and when the clutch is disengaged, (spring has a maximum deflection 12,6mm), the deviations on the stress that is measured there is deviations 0,8%. Deviations of the calculated values in the expressions Almen-Laszlo in relation to the measured value of stress is (- 15 ÷ +3)%, it is considered to be relatively good. Deviations of the calculated stresses by the method of finite element in relation to the measured value of stresses are (-12 ÷ -9) %, these results are quite satisfying.

Figure 12 shows a diagram of the change of the stress depending on the deflection of measured, calculated stresses after the expression ALMEN-LASZLO and calculated stresses method finite element.

The curve obtained by Almen-Laszlo equation deviates from the curve obtained by measuring. There is no similarity between these two curves because the stress increases gradually, according to the Almen-Laszlo equation, depending from the deflection. Deflection in a flat position is -15%, and when the deflection is maximum deviation is + 3%.

There is similarity between the curve obtained by FEM and the measurement curve, and it is good, but there are certain derogations. Deviation in flat position is -12% and in position at maximum deflection deviation is +9%. Reason for this derogation can be: the number of finite elements used in FEM, the quality of the spring (the material, its strength, hardness, quality workmanship, shot penning on the surface of the upper and /or lower side, dimensional derogation etc.). More of these parameters on the quality of the spring can not be taken in consideration when the calculation is performed by FEM.

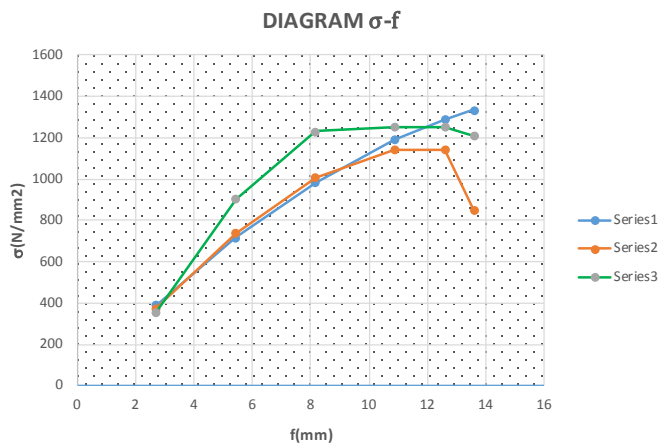


Fig. 12. Stress change depending on the deflection of calculated and measured stress. Series 1-after the calculating AL; Series 2-after the calculating FEM; Series 3-measured EXP

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MATERIAL DEFORMATION ANALYSIS IN BRIDGE CRANE DURING TRAVEL MOTION WITH FULL LOADING

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Abstract: This paper deals with dynamic analysis of bridge crane with single girder in order to determine material deformations in their main parts – cables and girder's, while moving and carrying load. It is known that these are mostly loaded parts in crane, while they accept forces, moments and oscillations from lifting mechanism and load. Analysis will be accomplished using computer modeling and simulations. Work process of crane in the study is forward travel motion. It is assumed that this motion process makes major impact in the deformations of lifting cables and girders due to stress, oscillations, and negative effect of load swinging. The analysis will be concentrated in finding the nature of oscillations that acts on crane and finding the extent and form of materials stress and deformations that can cause fatigue, failures and accidents. Question is whether acting loads exceed elasticity limits, or there are plasticity deformations which lead to permanent damages. Results will be shown in the form of diagrams, contour stress and strain in cables and girders. They will be compared with experimental measurements. Conclusions of these analyses can be useful for design considerations and safety.

Keywords: BRIDGE CRANE, SINGLE GIRDER, MATERIALS, DEFORMATIONS, TRAVEL MOTION, OSCILLATIONS, MODELING, SIMULATIONS

1. Introduction

Bridge crane is modeled based on manufacturer *Prim Co Company*, Type JP100 (Fig.1) [1]. Crane is mounted in rails in the walls of one factory. Max carrying load & Pulley system is $G = 5100 \text{ kg} = 50 \text{ kN}$. It has one main girder, and two side girders (left & right). Height position of girders is $H = 6.5 \text{ m}$. Length of main girder is $L_m = 12.2 \text{ m}$ (Fig.2). Length of side girders is $L_s = 2 \text{ m}$. (Fig.2). Velocity of crane $v_{cr} = 0.5 \text{ m/s}$. Velocity of telfer $v_{tr} = 0.33 \text{ m/s}$. Diameter of crane wheels $D_v = 200 \text{ mm}$. Crane is moving on 4 wheels, 2 per each side, mounted on side girders (Fig.1, 3). Before simulations, weight Q (workload) is in the position of relative rest at the height $H = 1.5 \text{ m}$ from basement.

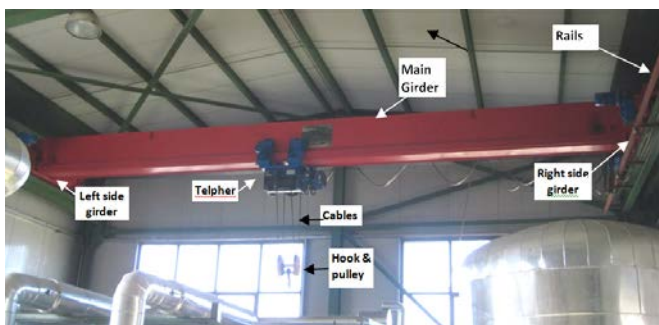


Fig.1. Bridge crane with parts in the work environment [1]

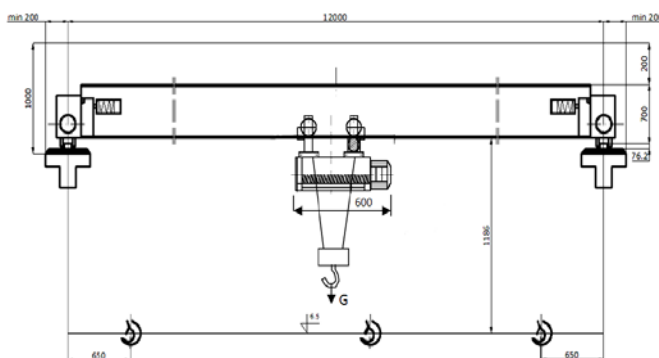


Fig.2. Bridge crane main dimensions [1]

2. Properties of Girders

- Main girder has profile (Cross section) of Hollow Box Beam, with thin wall section, with dimensions shown in Fig. 3. Material of Main girder is made of Steel S355 [11]. In most structural steel specifications the yield strength, ultimate tensile strength,

elongation and in some specifications also the Charpy V values are specified [10]. Mass of main girder is 2000 kg.

- Side girders have profile of partially Hollow Box, shown in Fig.3. Its bottom is open to mount wheels of crane. Material is also Steel S355 [11]. Mass of each side girder is 300 kg.

When load acts in girders, it will deflect and deform them. Main type of strain and deflection that acts on girders is bending towards vertical axes and shear. It is suggested that also torsion appears during forward traveling of crane, which we will search in this work.

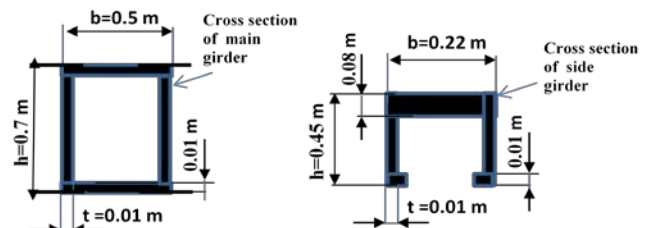


Fig.3. Cross sections of main girder and side girders

3. Modelling of Bridge crane

In Fig.4 is presented model of bridge crane done in software [4] including working environment, which is also modeled. Working environment includes metal frames, bars, rails and basement.

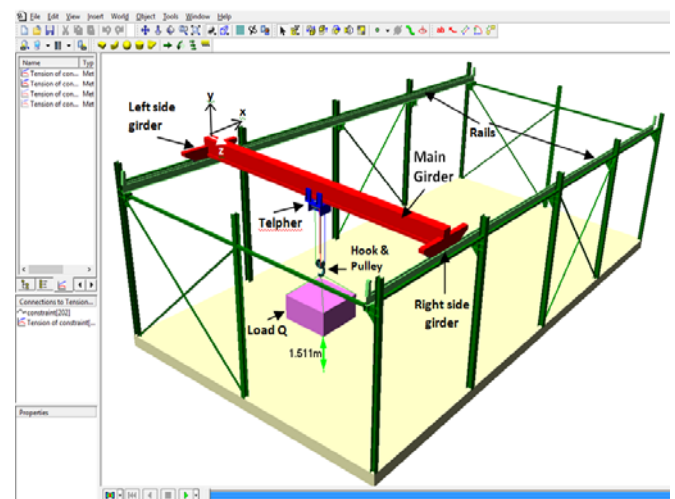


Fig.4. Model of bridge crane in the working environment where simulations will apply, created with software SimWise 4d [4]

Lifting mechanism is designed in the form of double pendulum. Working load has prismatic form with dimensions 2 m x 2m x 1 m, with mass $Q = 5000$ kg (including Pulley and Hook mass) (Fig.2) [7]. Load height from basement is 1 m. It is positioned in the center of main girder. We consider that best results will be achieved with max carrying load $Q = 5100$ kg, as given by manufacturer [1].

Crane's model of main girder and side girders, with side extensions for telpher is shown in Fig.5. [8], [3]

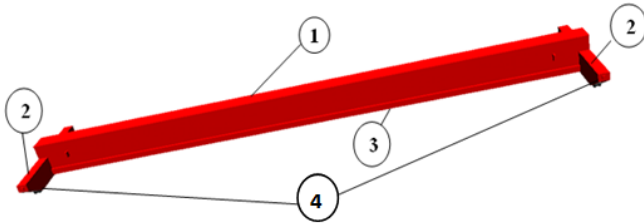


Fig.5. Model of main girder and side girders: 1-Main girder; 2-Side girders; 3-Side extensions for the laying telpher; 4-Crane wheels;

Simulations will be planned for crane traveling - translational motion for time $t = 8$ s, which converts to travel length $l = 4$ m. Simulations are planned to reflect real travel of crane in order to achieve reliable results and comparable with measurements. For the proper scenario of travelling process, simulation will start without travelling until time $t = 0.5$ s. This in order to have the stability of load hanging on cables. After $t=0.5$ s, will start the travel of crane with griven speed. Travelling will end on time $t = 8$ s, which converts in length $l = 4$ m.. (Fig.7) [4], [8].

4. Experimental measurements

Lifting cables are heavily loaded part, while they carry load and hoist mechanism. There are 4 branches of cables connected with Hook and pulley system, which connects to drum with 2 lifting branches. Measurements in crane are done in place where crane is mounted, in one local company (Fig.1). They will be used for validation of results [5]. Main measured parameter was tensile force in lifting/lowering cables – F_t . In this crane there are 4 branches of lifting cables connecting between drum and pulley system.

Type of cables are wire ropes type 6X37, with diameter $d_c = 19$ mm [1]. Other properties are: Modulus of elasticity: $E = 7.58 \cdot 10^{10}$ Pa, Minimum breaking strength $F_b = 212$ kN, Safe Load $F_s = 42.3$ kN [1], [14].

Tensile force was measured with dynamometer type Dini Argeo attached to the Hook [9], during motion of crane (Fig.6). There were 5 measurements achieved, and results are shown in Table.1:

Time of travel (s)	Tensile Force in all lifting cables - F_t (N)	Force in each branch of lifting cables ($F_t/4$) (N) (aprox.)
1	51800	12950
3	49800	12450
6	52700	13175
8	50600	12650
12	50750	12687

Table 1. Results of F_t with dynamometer in hanging cables



Fig.6. Measurements with Dynamometer during motion of crane

5. Results in lifting cables

In Fig. 7 is given graph of Force F_t in one cable branch after simulations of crane travel. Result are shown for time of crane travel $t = 8$ s.

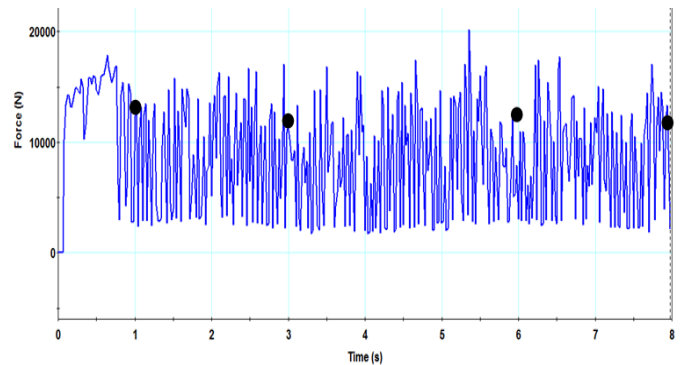


Fig. 7. Tensile force F_t in one branch of lifting cable. Black dots are experimental values from Table 1.

Based on graph in Fig.7, we can conclude that force in lifting cables during crane travel is comparable with experimental values, which are shown with black dots. This validates results with simulations and makes them reliable and trustworthy.

Graph of Force in cables is dynamic in nature, with high frequencies that reach up to $\nu = 17$ Hz, maximum value of force is achieved in time $t = 6.5$ s, with value $F_{dmax} = 20000$ N = 20 kN.

Based on literature, strength properties of lifting cables are: Minimum breaking strength $F_b = 212$ kN, Safe Load $F_s = 42.3$ kN [1], [14]. It can be concluded that $F_{max} < F_s$, cables of crane can stand the dynamic tensile force without major deformations.

But, value of dynamic coefficient Ψ , which is the ratio between maximal dynamic force and static force is high [6], [8] :

$$\Psi = \frac{F_{dmax}}{F_s} = \frac{20}{50/4} = \frac{20}{12.5} = 1.6$$

This results that cables undergo 60% more dynamic forces compared to static forces. This is a matter of concern while cables strength will decrease by time and express fatigue after defined time frame, which requires frequent control of their condition.

4. Results in main girder

Girders are considered most important part of Crane (Fig.1, Fig.2). On main girder is mounted telpher that hangs in side extensions (Fig.2,4), which has also mounted on it hoisting mechanism and load Q. Dynamics and oscillations from the load Q and hoisting mechanism are passed on girder.

Main parameters that define material loading deformations are stresses and strains based on acting forces and moments. Results of these parameters are most important for analysis and concusions.

Formula of normal stress for Hollox Box profile is [2], [10]

$$\sigma_x = \frac{M}{J_x} \cdot y \quad (2.1)$$

M - Bending Moment; J_x – Moment of inertia; y – position in the cross section.

$$\text{Max value of stress is: } \sigma_x = \frac{M}{W_x} \quad (2.2)$$

$$\text{Where } W_x = \frac{J_x}{y_{max}} = \frac{4}{3} \cdot b^2 \cdot t \text{ - resisting moment of inertia} \quad (2.3)$$

Formula of Shear stress for Hollox Box profile is:

$$\tau_{xy} = \frac{T_{max}}{J_x} \cdot \frac{S'}{t} \quad (2.4)$$

where: $I_x = 2 \cdot t \cdot h^3 / 12 + 2 \cdot (b-2t) \cdot t \cdot (h/2-t/2)^2$
 $S' = 2 \cdot h/2 \cdot t \cdot h/4 + (b-2t) \cdot t \cdot (h/2-t/2)$ (2.5)

T_{max} – max value of shear force; S' – Static moment of profile area
 h – height of profile area; b – width of profile area; t – thickness of profile walls [2], [10].

In the Theory of constructions using Finite Elements Method, and in calculation of stresses by software [3], there is implementation of Von Mises Stress, which is widely used by designers to check whether their design will withstand a given load condition. It is a value used to determine if a given material will yield or fracture. It is mostly used for ductile materials, such as metals. The von Mises yield criterion states that if the von Mises stress of a material under load is equal or greater than the yield limit of the same material under simple tension. General von Mises equation, using principal stresses is [12], [13]:

$$\sigma_v = \sqrt{\frac{1}{2}[(\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{33} - \sigma_{11})^2 + 6(\sigma_{12}^2 + \sigma_{23}^2 + \sigma_{31}^2)]} \quad (2.6)$$

Where stress componets are part of Cauchy stress tensor:

$$\sigma = \sigma_{ij} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix} \equiv \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix} \equiv \begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix} \quad (2.7)$$

Some of these textbooks for machine design show that the von Mises stress with respect to non-principal axes can also be expressed as [13]:

$$\sigma' = \frac{1}{\sqrt{2}} [(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)]^{1/2} \quad (2.8)$$

When only σ_x and τ_{xy} are present (as in combined torsion and bending/axial stress or pure torsion), the Von Mises stress is:

$$\sigma_v = \sqrt{\sigma_x^2 + 3\tau_{xy}^2} \quad (2.9)$$

Note that in pure shear or pure torsion $\sigma_x = 0$. If $\sigma_x = 0$, then:

$$\sigma_v = \sqrt{3\tau_{xy}^2} = \sqrt{3} \cdot \tau_{xy} \quad (2.10)$$

According to distortion energy theory, yielding occurs when σ_v reached the yield strength S_y . Therefore in pure shear, yielding occurs when τ_{xy} reaches 58% of S_y [12]. In further analysis, Von Mises stress and its components will be calculated and shown as main result for girders.

Results will be achieved using Numerical methods (Kutta-Merson) and Finite Elements Method (FEM), supported by software in order to achieve best results.

Other properties of main girder are: Elastic Modulus: $E = 2 \cdot 10^{11}$ Pa, Yield Stress $\sigma_{yi} = 3.31 \cdot 10^8$ Pa ; Ultimate Tensile Stress $\sigma_{ut} = 4.48 \cdot 10^8$ Pa ; Poisson's Ratio $\nu = 0.29$. [1]

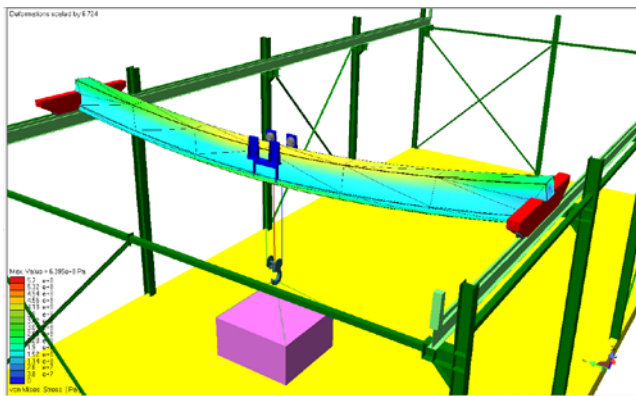


Fig.8. Deformation of main girder (Scaled by 6.274), and contour spread of Von Mises Stress

Based on model created, results are achieved for main dynamic parameters for measurement of deformations: *Stress and strain* [4], [8],[2]. Stress will be type Von Mises Stress. Results are shown in Fig.9 to Fig.12. In Fig. 8 is shown discretization of girder in volume FEM Elements, values of contour Stresses, and deformation of girder (Scaled by 6.274).

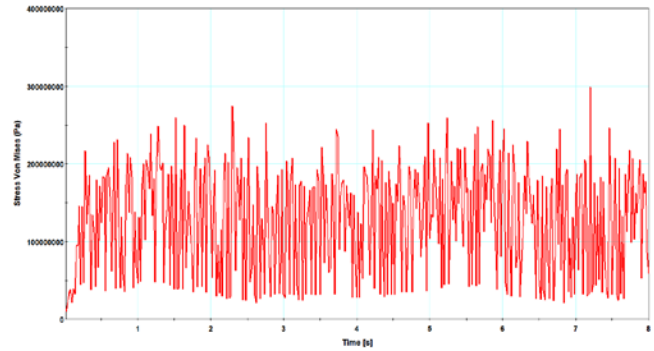


Fig.9. Stress Von Mises in main girder

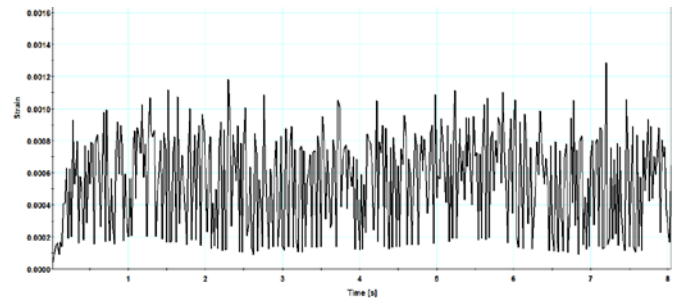


Fig.10. Strain Von Mises in main girder

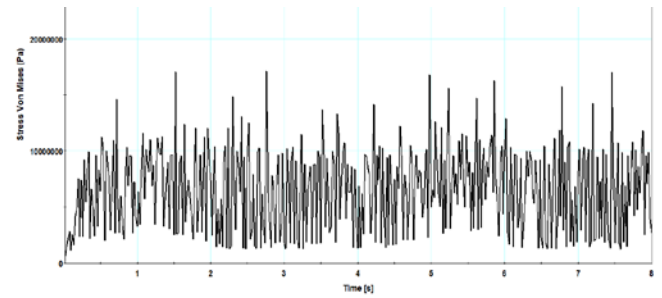


Fig.11. Torsion stress in main girder – τ_{xy} . Main girder undergoes torsion

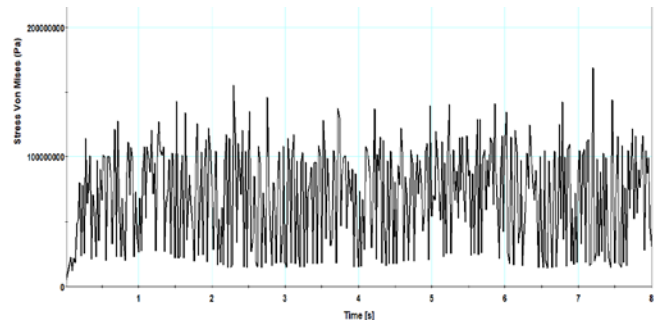


Fig.12. Shear stress in main girder – τ_{yz}

Based on results from Fig.9 to Fig.12, we can conclude that main girder undergoes heavy dynamic stresses and strain, with frequent oscillations, high amplitudes and high frequencies that reach up to $\nu = 18$ Hz. Max value of Von Mises stress occurs in time $t \approx 6.6$ s, and has value $\sigma_{max} = 3 \cdot 10^8$ Pa (Fig.9). This value of stress is less then Yield stress $\sigma_{max} < \sigma_{yi} = 3.31 \cdot 10^8$ Pa of material. This concludes that girder's structure can handle the loading, but is near to boundary Yield stress and near to possible deformations.

In Fig.10 is given graph of Strain for girder - ϵ . Graph is similar in form and dynamics of change with the one of stress. Max value of strain is $\epsilon = 0.0013$ occurring in time $t \approx 7.5$ s.

In Fig.11 is given graph of Torsion for girder. It can be concluded that girder is loaded with torsion, but the intensity is small, $\tau_{xy\max} \approx 1.3 \cdot 10^8$.

In Fig.13 is given graph of Shear stress for girder. Maximal Intensity is small, $\tau_{yz\max} \approx 1.5 \cdot 10^9$.

5. Results in side girder for travel motion

In Fig.13 to Fig.16 are shown graphical results for Right Side Girder. Results of graphs of Side Girder (Fig.14,15) are similar in form and dynamic occurrence with ones of Front girder.

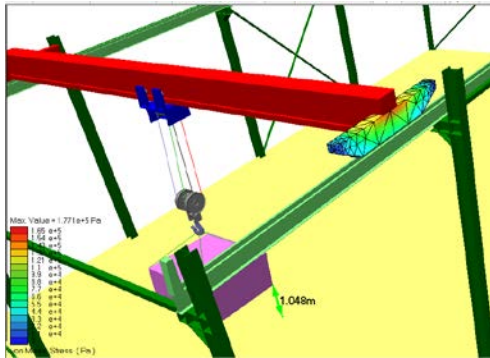


Fig.13. Contour spread of Von Misses stress in right side girder

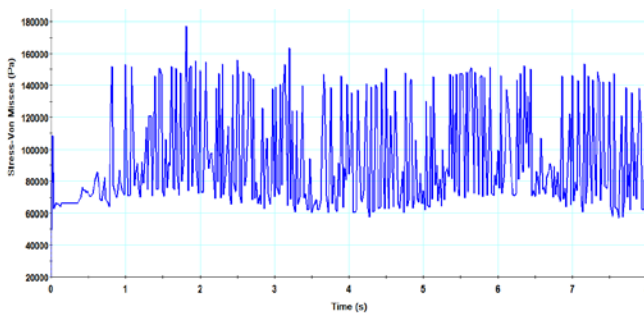


Fig.14. Stress Von Misses in side girder

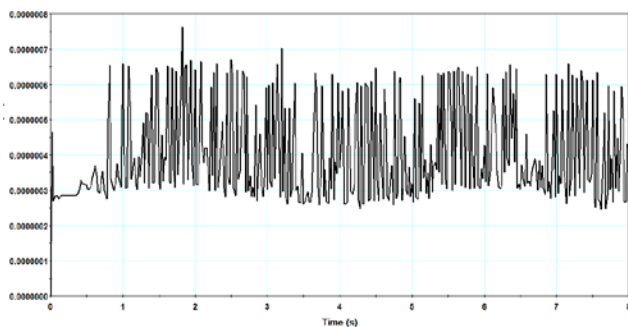


Fig.15. Strain Von Misses in right side girder

Based on results from Fig.14 and Fig.15, we can conclude that main girder undergoes heavy dynamic stresses and strain, with frequent oscillations and high frequencies.

Values of Von Misses Stress are smaller than for main girder (Fig.14). Max value occurs in time $t \approx 3$ s, and has value $\sigma_{\max} = 1.7 \cdot 10^5$ Pa (fig.9). This value of stress is less than yield stress of material $\sigma_{\max} < \sigma_{yi} = 3.31 \cdot 10^8$ Pa of material, which means that girder's structure can handle the loading.

In Fig.10 is given graph of strain for girder - ϵ . Graph is similar in form and dynamics of change with the one of stress, but values are smaller. Max value is $\epsilon = 0.0000007$ occurring in time $t \approx 1.8$ s.

Another important conclusion from results is that oscillations occurring on load Q and cables are passed in other parts of crane with similar form of curve, periods, and frequencies.

6. Conclusions

The main problem in bridge cranes during travel are oscillations as dynamic occurrences. It is important to identify and minimize them. Their influence will impact material deformations significantly. Oscillations in cranes often are difficult to measure with instruments. They are mainly induced by load and pulley swinging that induces forces in cables, and further other forces, moments and stress in other parts. To find their form of occurrence we created model of bridge crane and implemented simulations. Results are also compared with experimental analysis. Important part of analysis is finding proper simulations plan that reflects real crane's travel motion, so that results are reliable. Results are gained for main dynamic parameters that represent material loading and deformations. Based on results, it can be concluded that main parts of crane analyzed undergo oscillations that are heavy and mostly with irregular occurrence. They occur in different planes. They have negative effect in parts and deform them. According to results we can conclude that crane parts analyzed can handle dynamic loads and don't show problems of overload or plasticity deformations. But this is acceptable only if proper type of material is selected. Also long term oscillations of this form will decrease strength of parts and increase chances for fatigue and damage. It is important to minimize oscillations in order to achieve minimal dynamic loads [5], [8]. Speed of travel must remain in optimal value, as lower as possible to minimize negative effects of load swinging, deformations of parts and other safety considerations.

This work is also important for safety at work with bridge cranes. It can be used also for further material strength analysis, and in the future can be used for other work processes like load lifting and cart travel.

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INVESTIGATION OF THE PRODUCTION PROCESS OF TWO-LAYER POWDER PERMEABLE MATERIALS BY THE ION-PLASMA SPUTTERING METHOD

ИССЛЕДОВАНИЕ ПРОЦЕССА ПОЛУЧЕНИЯ ДВУХСЛОЙНЫХ ПОРОШКОВЫХ ПРОНИЦАЕМЫХ МАТЕРИАЛОВ МЕТОДОМ ИОННО-ПЛАЗМЕННОГО НАПЫЛЕНИЯ

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Abstract The investigation results of the production process of powder permeable materials (PPM) by forming thin permeable layers by means of ion-plasma sputtering method in a vacuum with the use of removable agents have been presented. The method makes it possible to obtain a continuous coating on the surface of the porous substrate. The layer formation on the surface of the porous substrate is provided by the use of the removable agent. After its removal, the layer sputtered on its surface remains an independent unit in the structure of the two-layer permeable material. The coating applied to the substrate has an open porosity.

KEYWORDS: POWDER PERMEABLE MATERIALS, ION-PLASMA SPUTTERING IN VACUUM, REMOVABLE AGENT, PROPERTIES

1. Introduction

Reduction of the thickness of a fine-dispersed layer of two-layer powder permeable materials (PPM) leads to a decrease of their hydraulic resistance and, accordingly, increases the efficiency of use [1, 2].

One of the methods that make it possible to produce double-layer PPMs is to apply thin permeable coatings to the porous powder substrate by ion-plasma sputtering method in a vacuum [3-5]. However, the significant dependence of the pore size of the thin permeable layer on the pore size of the substrate and the columnar nature of the coating (Fig. 1) do not encourage the formation of structures with a complex of properties that one would expect from this method.



Fig.1 The structure of the PPM produced by ion-plasma sputtering method in a vacuum without a removable agent

The purpose of this work is to study the production process of ion-plasma sputtering method in a vacuum using removable agents.

2. Materials

The samples were produced in the form of disks with a diameter of 30 and a thickness of 3 mm. A study of the structure of porous materials was carried out using a high-resolution scanning electron microscope "Mira" of Tescan company (Czech Republic) (Fig. 2);

the characteristics were determined by standard methods (average pore size according to GOST 26849-86, permeability coefficient in accordance with GOST 25283-93, porosity according to GOST 18898-89).



Fig. 2 A high-resolution scanning electron microscope "Mira-3" of Tescan company (Czech Republic)

Initially, a porous substrate was made from a tin-phosphorous bronze powder with particle sizes (minus 630 + 400) μm by a free-filling sintering method, then its surface pores were filled with a removable agent – NaCl powder with a grain size composition (minus 40 + 20) μm on one side of the substrate. To ensure better adhesion of the particles of the removed agent to each other and to the base material, a 5% solution of carboxymethylcellulose (CMC) in water was used as the binder. The ratio of CMC in a mixture of NaCl-CMC was 4% (volumetric). Then a copper coating with a thickness of 35 μm was applied on the side of the removable agent by the ion-plasma sputtering method in a vacuum on a vacuum plating machine HHB-6.6-И1. Then NaCl was removed and the average pore size and permeability coefficient of the produced sample were determined. The machine for the application of vacuum functional coatings HHB-6.6-И1 is shown in Figure 3.



Fig.3 A vacuum machine HHB-6.6-II1 for the application of vacuum composite functional coatings

3. Results and discussions

The choice of materials of the removable agent and binder is due to the fact that the object treated by ion-plasma flows in a vacuum should give stability (resistance to decomposition, no gas evolution, etc.) at temperatures up to 200 °C. It was confirmed by the study of the behavior of the NaCl-CMC composition at different temperatures in air. The porous structure of NaCl-CMC is shown in Fig. 4.

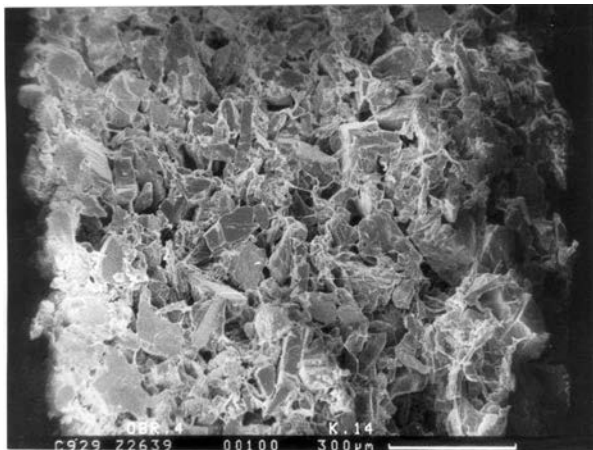


Fig. 4 The porous structure of NaCl-CMC

The main requirement for the composition of NaCl-CMC is the presence of through porosity in its structure and, accordingly, on the surface, otherwise the production of the effective two-layer PPMs by the method being developed will be problematic. Analysis of the structure of the obtained composition confirms the presence of through porosity (Fig. 4). In addition, to confirm the possibility of using the selected removable agent when a thin permeable layer was produced from the NaCl-CMC composition by the ion-plasma sputtering method in a vacuum with free-filling molding into a mold, a substrate was prepared which was coated with a thin layer of copper by means of ion-plasma sputtering and brittle fractures of the produced sample were investigated (Fig. 5-7).

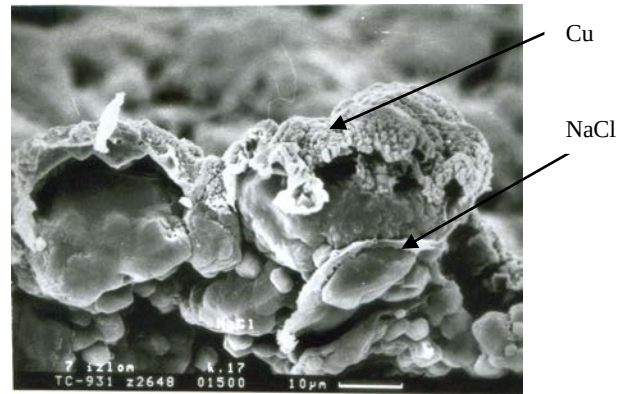
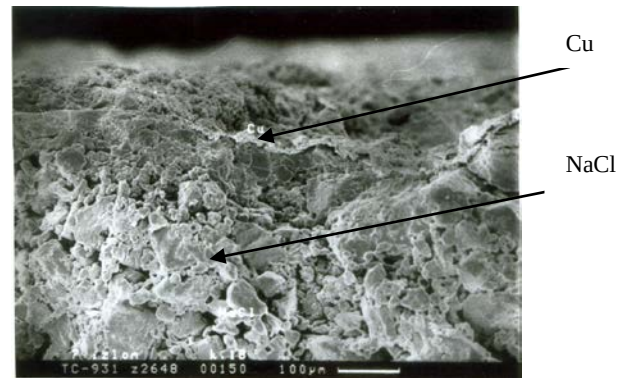
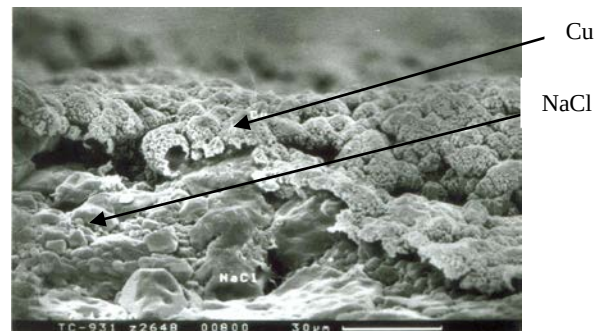


Fig. 5 The configuration of the coating on the removable agent, $\times 1500$



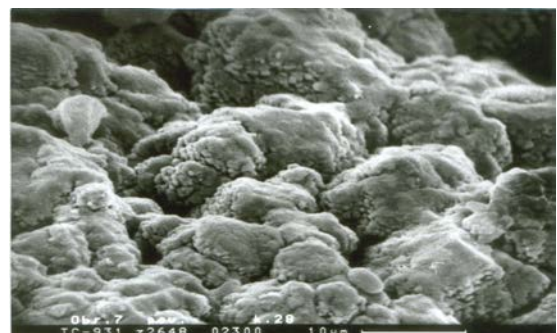
a)



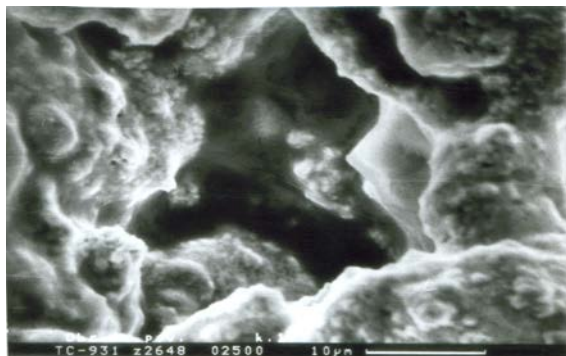
b)

Fig. 6 Copper coating on the NaCl-CMC composition at various magnifications, x : a) $\times 150$; b) $\times 800$

Figure 5 shows the configuration of the coating of individual particles of the removable agent with the sputtered material (copper), which repeats their shape. Figure 6 illustrates the presence of a thin continuous sputtered layer of copper on the surface of the substrate at various magnifications. Figure 7 confirms the presence of open pores on the surface of the substrate.



a)



b)

Fig. 7. Pore channels on the surface of the substrate produced from the NaCl-CMC composition, after applying a layer of copper at various magnifications: a) $\times 2300$; b) $\times 2500$

Analysis of images of brittle fractures obtained by the proposed method, experimental samples of two-layer PPMs and their surface on the side of the sputtered layer (Fig. 8-13) makes it possible to define that:

- the proposed method makes it possible to obtain a thin continuous coating on the surface of the porous substrate (Fig. 8);
- the creation of a thin layer on the surface of the porous substrate is primarily provided by the use of a removable agent: the images of the sample surface in the cracking site at the fracture (Fig. 9) and the fracture at the sites where the removable agent was sputtered (Fig. 10) show that after removal of the removable agent, the layer sputtered on its surface remains an independent unit in the structure of a two-layer PPM, sufficiently tightly bound to the porous substrate;
- the coating sputtered on the substrate has an open porosity (Fig. 11);
- the particles of the sputtered layer have a good contact with the substrate particles (Fig. 12) and with each other (Fig. 13).

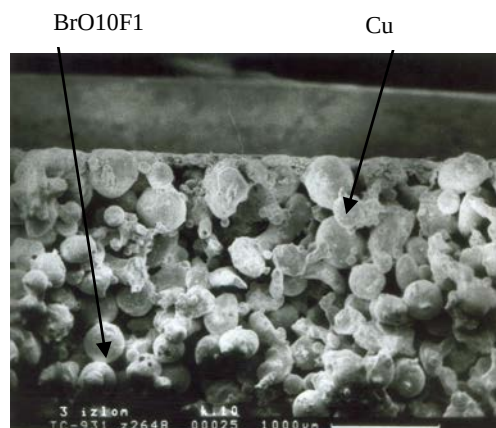


Fig. 8 Structure of a two-layer PPM, $\times 025$

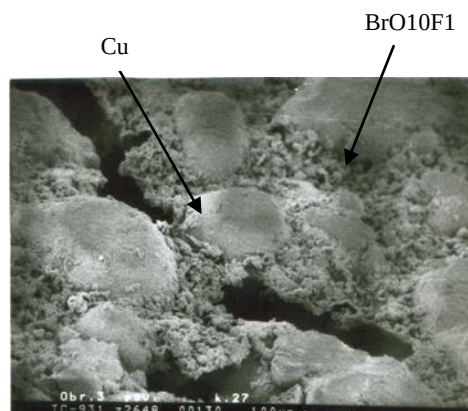


Fig. 9 Cracking at the fracture site of the experimental sample



a)



b)

Fig. 10 Fractogram of the brittle fracture of the experimental sample in the region of the removable agent at various magnifications: a) $\times 250$; b) $\times 300$



Fig. 11 Surface of the experimental sample when the thin permeable layer is applied

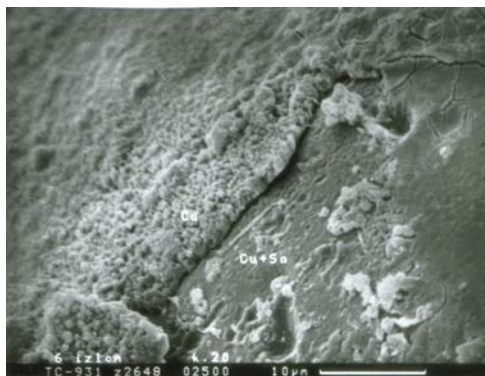


Fig. 12 The boundary line between the sputtered layer and the substrate particle at the site of brittle fracture



Fig. 13 The coating on the substrate particle (on the right) and on the removable agent (on the left)

The properties of the experimental samples of two-layer PPMs and also the properties of the analogue samples are given in Table 1.

Table 1 – Properties of two-layer experimental samples and analog samples

PPM Characteristics	PPM process					
	Ion-plasma sputtering in vacuum using a removable agent		Powder molding of various fractions		Ion-plasma sputtering in vacuum without a removable agents	
	The particle size of a removable agent, μm (minus 40+20)		Particle size of fine-dispersed layer, μm (minus 200+160) (minus 160+125)		The particle size of the substrate powder, μm (minus 630+400) (minus 400+315)	
	The particle size of the substrate powder, μm (minus 630+400) (minus 400+315)		The particle size of the substrate powder, μm (minus 630+400) (minus 400+315)			
	(minus 630+400)	(minus 400+315)	(minus 630+400)	(minus 400+315)		
Porosity, P, %	42	41	40	38	43	41
d _{н max} , μm	63	49	60	42	220	140
d _{н cp} , μm	38	27	38	27	170	120
k, m ² , ×10 ¹³	364	350	197	172	1400	900

Analysis of the experimental data presented in the table enables to state that ion-plasma sputtering in a vacuum with the removable agents makes it possible to produce two-layer PPMs with an increased complex of properties: the permeability coefficient at the specified average pore size of such materials can reach values by 1.85-2, 0 times higher in comparison with two-layer PPMs, produced by the method of powder molding of different fractions.

4. Conclusion

The process of applying of ion-plasma coatings on porous substrates using a removable agent was studied. It has been experimentally confirmed that the proposed method makes it possible to produce a thin continuous coating on the surface of the porous substrate. The formation of a thin layer on the surface of the porous substrate is primarily provided by the use of the removable agent. After its removal the sputtered layer remains an independent unit in the structure of the two-layer PPM, sufficiently tightly bound to the porous substrate. The coating sputtered on the substrate has an open porosity. The particles of the sputtered layer have good contact with the substrate particles and with each other.

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FINITE ELEMENT MODELING OF INCREMENTAL SHEET METAL FORMING OF ALUMINUM ALLOY AL 1100

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Abstract: Incremental sheet metal forming has been well-known as one of the flexible methods of forming metallic sheets, suitable for the production of prototypes or small batch sizes. Apprehending the deformation method in forming processes and selection of route parameters to avoid part failure are of vital importance, because marketing needs standard sound parts in a shortest possible time. This paper presents the study on the use of finite element modeling of incremental sheet metal forming of Al 1100 aluminum alloy to investigate the effect of tool diameter and step over on the forming induced stresses, part thickness distribution and forming forces. The results of finite element analysis are compared with experimental data while producing truncated pyramid parts. It has been shown that the developed finite element model is capable of providing reliable results in the prediction of the final thickness of the part, which matches the experimental results with a maximum discrepancy of 8%.

Keywords: ALUMINUM ALLOY, INCREMENTAL FORMING, FINITE ELEMENT METHOD, FORMABILITY

1. Introduction

In sheet metal forming industry, the mass production of different parts is usually done by using accurate but expensive punches and dies. In mass production, because of the large quantities of the produced parts, the cost per part becomes significantly small, which makes these processes economically feasible for sheet metal forming industry. However, when small batch sizes or prototypes are required, the cost per part increases drastically. This increased cost makes the conventional methods based on dies and punches not feasible anymore. Therefore, it is necessary to develop and implement new developing techniques to satisfy the requirements imposed by the small batch production industries¹. Incremental sheet forming (ISF), which originates from hybridization of stretch forming and conventional spinning processes², can be considered as a plastic forming process which meets the requirements of individual part or small-batch production, enabling the manufacturing of the desired shape through an incremental localized deformation³.

In ISF process, the forming of a metal sheet is performed using the movements of a CNC controlled hemispherical head tool, which plastically deforms the blank according to a predefined path. The tool path generated with computer aided manufacturing (CAM) software, makes it possible to obtain complex geometries using a simply shaped tool^{1,4,5}. In addition to eliminating a need for sophisticated forming tools, ISF results in an increased forming limit compared to pressing process⁴. Due to its unique advantages such as flexibility, cost effectiveness as well as reduced time-to-market and increased forming limit, ISF has gained a substantial attention from academia and industry as an important research area. According to Jackson & Allwood⁴, and Jeswiet et al.⁵, the first industrial emergence of ISF which is also called "diless forming", dates back to 1960s in the USA. This method has been patented by Roux⁶ and Leszak⁷, while academic research lagging behind industrial application began in the early 1990s in Japan.

Depending on the complexity and desired accuracy of the workpiece, several variations of ISF have been developed in the last decades. In general ISF process can be classified into three groups, i.e. Single-Point Incremental Forming (SPIF), Two-Point Incremental Forming (TPIF), and Hybrid Incremental Forming (HISF).

SPIF, which is the simplest form of ISF, uses a simple tool to form the sheet, without requiring any supporting tool or die. The idea of using a fixed tool as a support has been introduced by

Matsubara in 2001⁸, where a very straightforward and compact tooling is devised and put on the bed of a CNC machine acting as a support during the forming process. The method which later called as TPIF has been successfully used in the forming of an aluminum sheet into cones and pyramids having an arbitrary number of sides with a minimum half-apex angle of 10°. The TPIF process may use a partial die or a full die. It should be mentioned that due to the reduced forming forces of ISF, it is possible to use soft materials such as plastics as partial or full dies, which can easily be produced by 3D printing techniques⁹. The term Asymmetric Incremental Forming (ASIF) is used to refer to both SPIF and TPIF⁵.

Due to the unique advantages of ASIF, recently extensive researches are done to understand the mechanism of forming of ASFI and its potential applications for the fabrication of either prototypes or functional parts. The studies in the literature are mostly concentrated on three important quality measures of the process, namely geometric accuracy, surface quality and formability. Low part accuracy due to spring back and sheet bending has been considered as a limiting factor for the industrial application of ASIF¹⁰, which is directly affected by the tool path generated by CAM software.

Finite element method has been used as an indispensable tool by several researchers to study ISF process. Cerro et al.¹ used FEM modeling of the ISF process of Al 1050-0 sheets during forming of pyramids with a 75° wall angle using the ABAQUS/Explicit software with shell elements. They reported a maximum difference of 5% between the peak values of the measured and predicted forming forces in the Z direction. The compromise between speed and accuracy of SPIF has been investigated by Yamashita et al.¹¹ using a dynamic explicit finite element code DYNA3D in forming quadrangular pyramids. The TPIF with full die has been studied by Attanasio et al.¹² to understand the effect of tool path type, step depth and scallop values on manufactured part characteristics. They investigated the surface quality, thickness distribution and geometric accuracy of a door handle of a commercial car made of FeP04 steel with a thickness of 0.7 mm. Their results showed that step depth and scallop height significantly influence the characteristics of the manufactured parts. They also presented some preliminary FEM simulations.

In the present paper, deformation behavior of Al 1100 aluminum alloy sheet metal in a single point incremental forming process (SPIF) is numerically simulated using ANSYS software. The effect of tool diameter and step over on the forming induced stresses; part thickness distribution and forming forces are

investigated. The results of finite element analysis are compared with experimental data while producing truncated pyramid parts.

2. Materials and Methods

In this study, SPIF of Al 1100 aluminum alloy is well-thought-out. Before conducting SPIF tests, the material properties are obtained using a standard uniaxial tensile test. An annealing process is carried out in the samples at 380 °C for 90 minutes. Fig. 1, illustrates the stress-strain curve for Al 1100 aluminum alloy. The material properties of this alloy are shown in Table 1.

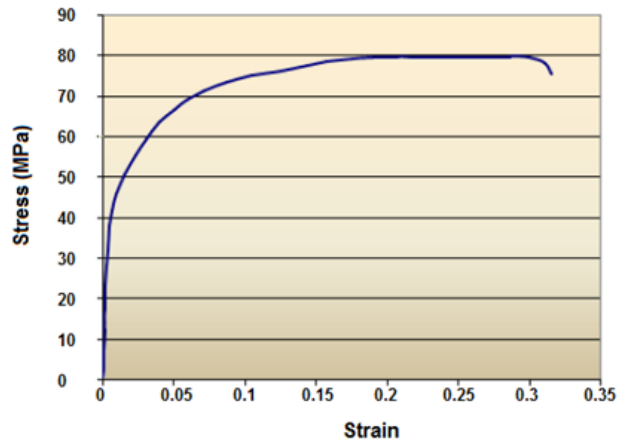


Fig. 1 Stress-strain curve for aluminum alloy Al 1100

Table 1: Material properties of aluminum alloy Al 1100

Elastic Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation %
84	0.33	41	79.7	31.8

To do single point incremental forming, aluminum sheets with dimensions of 150×150×1 mm are prepared. A forming tool with a diameter of 10 mm with a hemispherical head is fabricated from a Stellite (cobalt-chromium alloy) with a hardness of 54 HRC and mounted on a CNC milling machine (FP4MK-MST). The hemispherical part of the forming tool has been ground and polished to reduce the friction. The aluminum sheet is fixed to the CNC milling machine using a dedicated fixture. Fig. 2 illustrates the forming tool and experimental setup used in this study. A CAM software is used to generate a tool path using parallel spiral outside-in strategy. The tool path is schematically shown in Fig. 3.

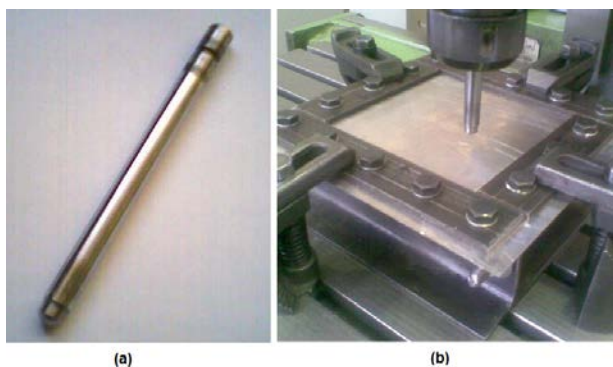


Fig. 2 (a) Hemispherical tool, (b) Experimental Setup for SPIF

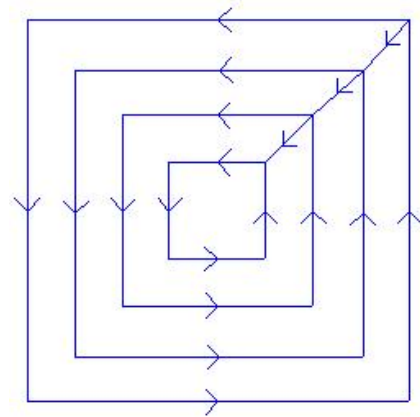


Fig. 3 The tool path used in the incremental forming process

The forming operations are performed at a feed rate of 60 mm/min with lubrication to reduce the friction and to avoid tool wear. The rotational speed is taken as 140 RPM. Fig. 4 illustrates a truncated pyramid part produced by SPIF process.

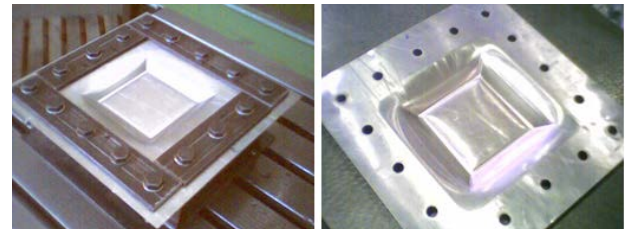


Fig. 4 (a) Truncated pyramid part fabricated by SPIF process

3. Finite Element Modeling of SPIF Process

In this study, finite element simulation of single point incremental sheet metal forming is performed using ANSYS software. The geometric model of SPIF process consists of four different parts, including forming tool, blank, blank holder and fixture as depicted in Fig. 5 (a). The fixture and blank holder are meshed using Solid 95 elements. The blank has been modeled using Visco Solid 107 element. The forming tool is modeled as an elastic body with a modulus of elasticity of 207 GPa. The meshed model of the assembly is shown in Fig. 5 (b).

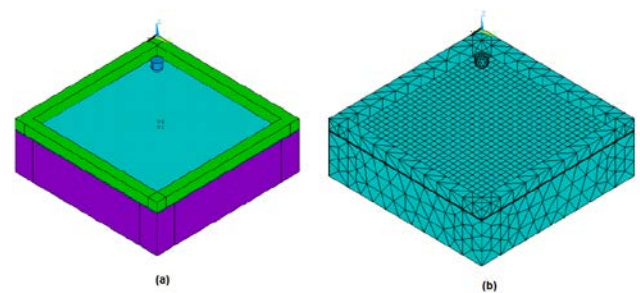


Fig. 5 (a) Geometric model of the SPIF process, (b) Finite element model of the SPIF process

A rigid-flexible surface-to-surface contact is defined using Target 170 and Contact 174 elements. Since in this process lubricant is used to reduce the friction between sheet and forming tool, a small Coulomb friction factor of 0.04 is used in the simulations. A step over of 10% of tool diameter is considered, meaning that after completing each loop the forming tool moves 1 mm from the current loop towards the center of the part to start the next loop. Fig. 6 illustrates the deformed shape of the sheet at the end of the simulation.

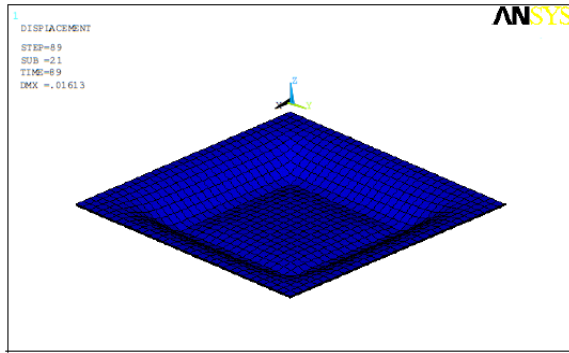


Fig. 6 Deformed shape of the sheet after SPIF process

The contours of von Mises stresses and strains are shown in Fig. 7 and Fig. 8, respectively. The results of simulations revealed that as the depth of part increases the level of stresses increases. The maximum stresses occur at the contact region between the forming tool and sheet during deformation.

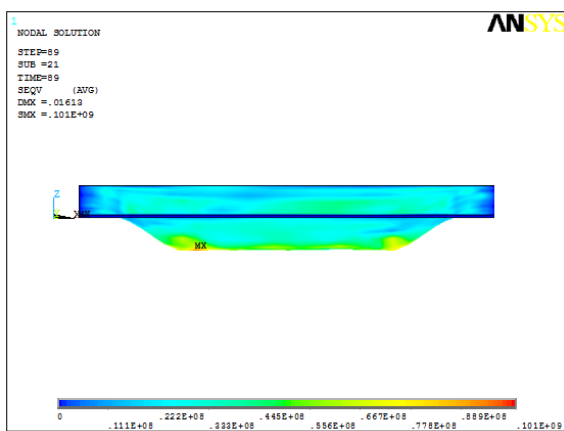


Fig. 7 Forming induced von Mises stresses in SPIF process

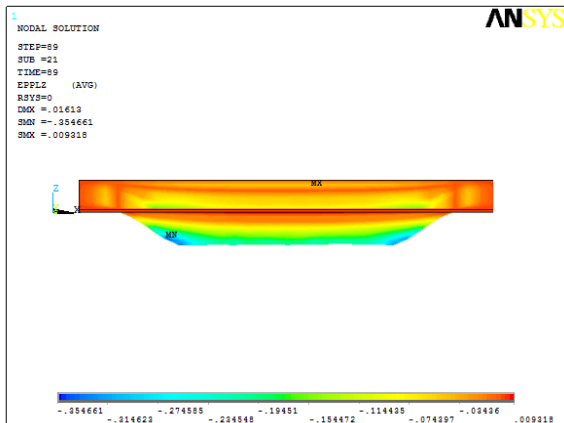


Fig. 8 Forming induced strains in SPIF process

The thickness of the part was measured at different positions to compare the results of simulations with experiments. Table 2 shows a comparison between experiments and finite element predictions. As is seen in Table 2, the minimum thickness in FEM predictions is about 0.65 mm, while it is 0.7 mm in experimental one, which shows the capability of the FEM model in the prediction of thickness reduction with a maximum error of 8%.

Table 2: Measured thicknesses vs. calculated thicknesses

Thickness FEM [mm]	0.65	0.73	0.81	0.89	0.97	0.99
Thickness Exp. [mm]	0.7	0.77	0.84	0.91	0.96	1

4. Analysis of the Effect of Forming Tool Diameter

The SPIF process was simulated with hemispherical head forming tools having three different diameters of 7 mm, 10 mm and 13 mm to analyze the effect of forming tool diameter in the incremental forming process. For each of forming tools, von Mises stresses, formed thickness and forming forces are obtained at a constant step over/outstep of 1 mm. The simulation results for each tool are shown in Table 3.

Table 3: Results of simulations for different tool diameters

Tool Dia. (mm)	Von Mises Stress (MPa)	Thickness (mm)	Maximum Forces (N)	
			F Feed	Fz
7	102	0.64	290	673
10	101	0.65	292	681
13	99	0.66	297	718

As it can be seen in Table 3, the increase in the forming tool diameter results in a decrease in the von Mises stresses and increase in the formed thickness of the workpiece. Therefore, we can conclude that with increasing forming tool diameter the possibility of failure reduces, which makes it possible to produce parts with larger depths. It can also be seen that, by increasing forming tool diameter both in-feed and in-depth forming forces increases.

5. Analysis of the Effect of Step Over

Step over is another important parameter which has a significant influence on the forming induced stresses and formability of the sheets during ISF process. In this study, the effect of step over on forming induced stresses and thickness reduction is considered. Two step over values of 10% and 20% are taken into account for a forming tool of 10 mm diameter, while other conditions are kept similar. The results revealed that by increasing step over from 10% to 20%, von Mises stresses increases from 101 MPa (Fig. 7) to 109 MPa (Fig. 9). The thickness of the part also reduced to 0.62 mm, meaning that as step over enlarges the formability of SIF decreases. Therefore, based on these results, in order to increase the formability, the step over values should be made as small as possible, however by selecting very small step over values, the processing time increases, which in turn reduces the productivity. Hence, the best compromise between step over and the process time is well-thought-out.

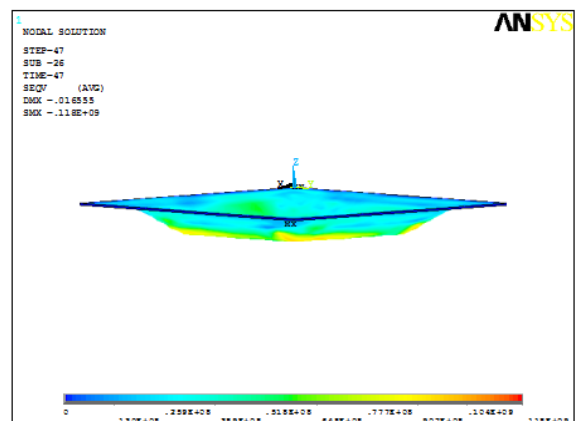


Fig. 9 Analysis of the Effect of Step over process

Conclusions

This paper aims at studying the use of finite element modeling of incremental sheet metal forming of Al 1100 aluminum alloy. To investigate the effect of some process parameters on residual stresses and part thickness distributions, the results of the finite element analysis are compared with experimental data while producing truncated pyramid shaped parts. It has been shown that the developed finite element model is capable of providing reliable results in the prediction of the final thickness of the parts, which matches the experimental data with a maximum discrepancy of 8%. The results of FE simulations revealed that with increasing forming tool diameter the possibility of failure reduces, which makes it possible to produce parts with larger depths. It has also found that by increasing forming tool diameter both in-feed and in-depth forming forces increases. The effect of step over on the formability of SPIF process of aluminum alloy Al 1100 has also studied. The results revealed that, as far as the productivity of the process is maintained, small step over values should be preferred to increase the formability and to reduce the forming induced stresses.

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THE INDUSTRIAL TEST OF CONCENTRATION OF CONCENTRATION OF SLOWLY COOLED CONVERTER SLAG

ПРОМЫШЛЕННЫЕ ИСПЫТАНИЯ ПО ОБОГАЩЕНИЮ МЕДЛЕННО ОХЛАЖДЕННОГО КОНВЕРТОРНОГО ШЛАКА

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Abstract: Nowadays are very actual problems of working out waste of non-ferrous metallurgy such as converter slags of the copper enterprise. One of the new direction of additional extraction of copper from slags of converter section is combine method including mechanochemical activation and concentration by flotation of nanostructured initial material. The first stage - is receiving thin crumbled material with high degree of dispersion. This permit furnish an explanation of noticeable changing of properties of high dispersion materials: appearance of activity centers on the surface of minerals because there are alterations and become activity of electronics structures of surfaces layers as consequence of modification of surface. Moreover, take places processes of opening of capsules, including captured particles of some components (metals, minerals from slag, such as copper sulphides etc.). As far as, converting is going with high speeds it's possible mechanical capturing of initial particles which didn't participate in interaction during of process converting, minerals may be screened by slag melt. Under the condition of the slowly cooling predominated kinetic mechanism of heterogenic interaction in the silica-containing system. On the basis of investigations was worked out the technological regulations and fulfilled the industrial probation.

KEYWORDS: CONCENTRATE, SLOWLY COOLED CONVERTER SLAG, FLOTATION, COPPER, EXTRACTION.

1. Introduction

One of the new direction of the additional extraction of copper from slags of converter section is the combine method, which includes mechanochemical activation and concentration by flotation of nanostructured initial material.

The converter slag was slowly cooled after converter in special cups during 3-4 twenty-four hours and then it was transported on storage-place. The large blocks 400-500mm were treated in crusher after that it were growing small in mill.

The first stage is receiving the thin crumbled powdery material with high degree of dispersion. This permit an explanation a noticeable changing of properties high dispersion materials: appearance of activity centers on the surface of minerals because there are alterations and activity of electronics structures on the surface layers as consequence of modification of surface. Moreover, take place processes of opening of capsules including of particles of components such as metals, minerals from slag: copper sulphides etc. As far as treatment in converter is going with high speed it's possible the mechanical capturing in the silica melt the initial particles which did not took part in interaction during of process converting, sulfides may be screened by slag melt. Under the condition of slowly cooling the kinetic (dynamic) mechanism of heterogenic interaction in system is predominated [1-5].

Slag includes the complex components, anions, ions etc. because there are different silica-oxygen complexes in slag. It's analogy of cooling melt of magma. The phase composition of slag is very complex because there are mobile equilibrium take place between different silica-oxygen complexes which defined by quantity solved oxygen in melt. It's observed polymerization of the metasilica complex: $n[\text{SiO}_3]_{2n} + n\text{O} = n[\text{Si}_2\text{O}_7]\text{SiO}_2$ which adding oxygen is forming groups of $[\text{SiO}_3]$: $n[\text{SiO}_3]: n\text{SiO}_2 + n\text{O} = [\text{SiO}_3]_n$; it's possible formation of complexes $[\text{Si}_2\text{O}_5]$ in accordance with scheme: $2n\text{SiO}_2 + n\text{O} = [\text{Si}_2\text{O}_5]_n$.

Moreover, it's possible capsulation of sulphur-containing minerals such as CuS , Cu_2S , CuFeS_2 etc. The mechanochemical activation is promoting increase of interaction in system.

The phase composition of slag is very complex and the mechanochemical activation create additional conditions for direct opening minerals of copper.

2. Fulfilment tests

Tests were carry out on Balkhash plant in accordance with program of testing. At first during of five twenty-four hours was taken about 1500 ton of the slowly cooled converter slag. It was used new regime cards, control of the regime parameters fulfilment by the Laboratory of technological investigations of Balkhash Enrichment factory. Results of tests (volumes products and per-two hours analysis) duration of tests were taken from reports of service of the Enrichment factory in accordance of timely inventory registration. The timely registration fulfilment at every day. There are results of tests presents in tables where show characteristics of products, simples, contents metals, productivity etc. [6-8].

The growing small initial material passed two stages with classification in hydrocyclone into closed cycle after the first stage of growing small on class - 0,074mm up to 55%. After the second stage the community very small crusing slag of class - 0,074mm up to 92-94% was given into between stage of flotation. Concentrate after that was given as a ready product and directly into apparatus of thickening. The tailings, which received between stages of flotation directed into the third stage of additional community to lump size of class - 0,074mm up to 90-95%. It was defined in average in initial material 5-6% Cu, in tailings 0,58-0,64%, degree of extraction by additional concentration preliminary 90-95% Cu.

Further in process of investigations was reached higher results (Table). At 04.11, 06.11, 07.11 were reached high degree of extraction cooper from concentrate: 94,7; 95,1; 95,9 accordingly (Table). Quality of concentrate is 25,4%

In accordance with the general probation which was at 5 November 2014yr. till 16-00 hour, when treated the slowly cooled slag received meaning of extraction cooper 95,0% and content cooper in initial slag 5,69%, in tailings (waste) 0,58% Cu and quality of concentrate 33,9% Cu.

Data	Time	Initial Cu in waste %	Tailings, %	Extraction Cu., %	Concentration, %	0,074 MM	Was treated, t
01.11. 2014	02.00	1,74	0,43	77,6	14,6 (6-8)		40
	04.00	2,22	0,42	82,4	14,5 (6-8)		40
	06.00	4,27	0,45	91,5	14,6 (6-8)		45
	08.00	4,31	0,75	85,7	14,7 (6-8)		40
	Shift	1,74/1,78	0,40/0,53		23,40/24,64	58	165
	10.00	2,68	0,62	78,7	25,9		55
	12.00	2,48	0,84	68,1	29,1		55
	14.00	2,71	0,69	77,6	17,6		55
	16.00	4,7	0,61	89,6	21,59		55
	Shift	3,24/3,36	0,69/0,73		22,48/23,49	67	220
	18.00	5,49	0,63	92,9	24		56
	20.00	3,76	0,63	95,6	22,9		56
	22.00	4,15	0,62	89,4	23,4		56
	24.00	6,29	0,59	93,0	22,8		55
	Shift	4,93/5,12	0,61/0,65		/22,71	65	223
02.11. 2014	02.00	4,72	0,57	90,9	17,2		59
	04.00	4,86	0,59	91,4	15,4		59
	06.00	4,09	0,57	94,8	18,4		59
	08.00	6,62	0,57	94,1	19,6		59
	Shift	5,04/5,27	0,56/0,58		17,19/17,50	47	237
	10.00	4,97	0,53	92,8	19,5		52
	12.00	5,38	0,54	92,6	19,1		52
	14.00	4,8	0,58	91,1	16,5		53
	16.00	4,82	0,58	92,7	14,4		50
	Shift	4,84/4,96	0,58/0,61		17,4/17,41	52	207
	18.00	5,23	0,54	92,8	16,1		52
	20.00	5,8	0,59	93,3	15,95		52

Table 1. The journal of work out. An examples of control technological parameters

Results of the operating control given in table 1 (For example). During of industrial test of the slowly cooled converter slag accordance with average operating calculation shows, that initial maintenance Cu is 4,72%, in tailings – 0,57%, degree of extraction 92,4% Cu and quality of concentrate 27,4% Cu.

Table 2. Dynamic of changing degree of extraction copper in to concentrate in during tests

Date	Degree of extraction of Cu, %	Remark
01.11.14	93,3	An average volume took
02.11.14	94,1	in accordance of 5-6 measurements
03.11.14	93,9	on day
04.11.14	94,7	
05.11.14	95,0	
06.11.14	95,1	
07.11.14	95,9	
08.11.14	92,8	
09.11.14	93,7	

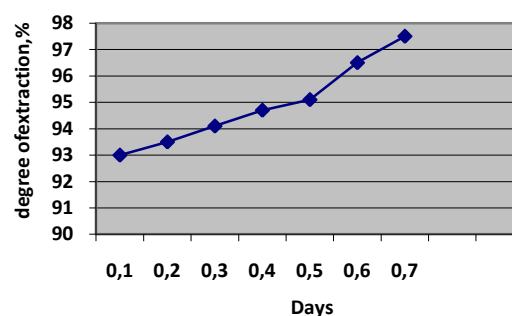


Figure 1. Dynamic of changing degree of extraction copper into concentrate

So, process of an extraction and concentration copper from waste of converter division of the copper enterprise include the basic flotation, one stage of sour operation and the control flotation. Concentrate of the sour flotation given into thickener as a ready product, tailings of scour and camera product of the control flotation recycling with tailings between stages of

flotation into the third comminute, tailings of the control flotation go to waste.

3. Conclusions

1. It was worked out the industrial tests of concentration of the slowly cooled converter slag and fulfilment estimation results of additional extraction cooper from the converter slag.

2. In accordance with the general probation treated the slowly cooled slag and received meaning of extraction cooper 95,0%, content cooper in initial slag 5,69%, in tailings (waste) 0,58%Cu and quality of concentrate 33,9%Cu.

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EXPERIMENTAL INVESTIGATION AND FUZZY LOGIC MODELING OF 8X8 CM² MEMBRANE PERFORMANCE OF MICROBIAL FUEL CELL

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Abstract: In this study, microbial fuel cell's energy conversion performance experimentally investigated from the chemical energy of the organic waste to electrical energy by means of microorganisms. Microbial fuel cell (MFC) consists of two cells which has 15x15x15 cm³ volume. One part of the cell conserves the mud (anode) the other part conserves the water (cathode). The membrane of the microbial fuel cell has 8x8 cm² area. Two different samples were used in the experiments which are active and settlement mud. The power, volt and current values of the active and settlement mud for different temperature, resistance and bubble were determined. The temperature values consist of $\Delta T = 8^{\circ}\text{C}$, $\Delta T = 10^{\circ}\text{C}$, $\Delta T = 12^{\circ}\text{C}$, $\Delta T = 14^{\circ}\text{C}$. $\Delta T = T_{\text{environment}} - T_{\text{mud}}$. For every ΔT value 2 different bubble values were examined (High=21,5 g/h, low=3,5 g/h). For every bubble effect 7 different resistance values were determined (1. Resistance= 3,75 Ω ; 2. Resistance = 7,5 Ω ; 3. Resistance = 10,5; 4. Resistance = 14,5 Ω ; 5. Resistance = 16 Ω ; 6. Resistance = 19 Ω ; 7. Resistance = 21,5 Ω) and the performance of the 8x8 cm² membrane of the MFC is detected. As a result; with the increase of the temperature, resistance and bubble effect the voltage production increases and correspondingly the current decreases. When all the experimental results are evaluated, the highest voltage production (687 mV) occurred at $\Delta T = 14^{\circ}\text{C}$ and 21,5 Ω with the high bubble effect in the settlement mud. Also, in this study, MFCs performances in terms of voltage, current, temperature, power was modeled with Rule-Based Mamdani-Type Fuzzy (RBMTF) modeling technique. Input parameters ΔT and time; output parameter power was described by RBMTF if-the rules. 1792 experimental data sets, which obtained for power according to ΔT and time, were used in the training step. The comparison between experimental data and RBMTF is done by using coefficient of multiple determination (R^2). The actual values and RBMTF results indicated that RBMTF can be successfully used in MFC.

KEYWORDS: MICROBIAL, FUEL CELL, FUZZY LOGIC, ACTIVE MUD

1. Introduction

Fuel cells are developed systems which use hydrogen as a fuel to generate electrical energy. During the energy production no combustion or exhaust gases occur because fuel cells combines hydrogen with oxygen into an electrochemical process to produce electric current. Hence one can say fuel cells are environment-friendly [1].

Microbial Fuel cells (MFCs) –one type of FCs- generate bioelectricity using an active microorganism as a biocatalyst in an anaerobic anode compartment. Active biocatalyst in the anode oxidizes the organic substrates and produces electrons and protons than the protons re transferred to the cathode chamber which is physically separated by a proton exchange membrane (PEM) from the anode chamber, and the electrons are conveyed through the external circuit. While oxygen reduces the protons and electrons are reacted in the cathode chamber [2].

Scientists have discovered almost a hundred years ago that bacteria can generate electricity. Nonetheless Microbial Fuel Cells that can produce electricity from organic matters from what would otherwise be considered waste, have been discovered as a new form of renewable energy technology. MFCs use energy much more efficiently than standard combustion engines -which are limited by the Carnot Cycle- and MFCs emissions are well below regulations. The new MFCs convert hydrogen to energy 8 times as high as traditional hydrogen production technologies therefore their energy efficiency is far beyond 50% [3].

In this study, experimental investigation was carried out to determine microbial fuel cell membrane performance. Two different samples were used in the experiments which are active and settlement mud. The power, volt and current values of the active and settlement mud for different temperature, resistance and bubble were determined. Also, in this study, Rule-based Mamdani-type fuzzy (RBMTF) modeling used to evaluate performance of MFCs. Performance parameters are power, current, voltage, temperature and bubble effect. In the developed RBMTF system, outlet parameter power was determined using inlet parameters time, temperature and bubble effect. The rules, which are used to detect

the behavior of the fuzzy logic controller and the relationship between system's input and output, are determined. As a result of these rules, every value obtained from the experimental study is also determined by fuzzy logic too. Main objective of the study is to present that it is possible to evaluate performance of MFCs by generating a fuzzy logic model.

2. Material and Models

MFCs use bacteria as the catalysts to oxidize organic and inorganic matter for generating current. The electrons are produced by the bacteria and transferred to the anode (negative terminal) and flow to the cathode (positive terminal). These two terminals are linked by a conductive material containing a resistor, or operated under a load (i.e., producing electricity that runs a device) as shown Figure 1 [4].

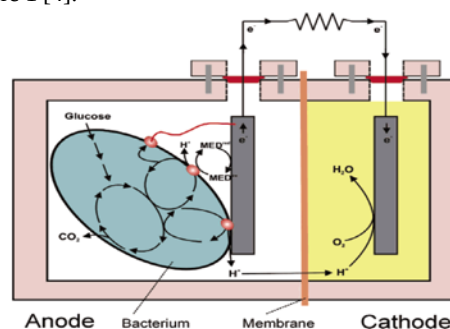


Fig. 1. Operating principles of MFCs [4]

In 1965 Zadeh introduced the fuzzy subsets theory as an extension of the set theory by the replacements of the characteristic function of a set by a membership function whose values range from 0 to 1. RBMTF is fundamentally a multi-valued logic that allows traditional evaluations like yes/no, true/false, black/white, large/small, etc. to be defined as notions like “rather warm” and

“pretty cold” and formulate these evaluations mathematically and process them with computers. A fuzzy system is based on three basic concepts; a fuzzy set, fuzzy membership and fuzzy variable. According to the classic theory of sets, if an element is in the set than its logical value is “1” and if an element is not in the set than its logical value “0”. Fuzzy IF-THEN rules is the knowledge base of RBMTF which are used to describe the functional dependencies between the input and output variables, following the reasoning with the operators AND, OR and NOT in general linguistic usage [5].

In this study, RBMTF was designed using MATLAB fuzzy logic toolbox. This model is constructed into RBMTF using input, time (s), temperature ($^{\circ}\text{C}$) and bubble effect; output parameter power (mW) described by RBMTF if-then rules for each sample. Numerical parameters of input and output variables were fuzzified as linguistic variables: very very low (L1), very low (L2), low (L3), negative medium (L4), medium (L5), positive medium (L6), high (L7), very high (L8) and very very high (L9).

3. Result and Discussion

MFCs are a special type of FC that the microbes added can purify wastewater and convert organic matter into electricity at the same time. Thus may offset the operating costs of wastewater plant. A MFC has separate anode and cathode chamber which in anode the organic material is oxidized by the microbes and in anode the electrons are transferred to cathode either by an added electron carrier or directly from the respiratory enzyme of the bacteria (mediator less). The transport of the electrons is done by external circuit where electrons are consumed by terminal electron acceptors [6].

The aim of this study, with the aid of experimental data, MFCs performances in terms of power, temperature, time and bubble effect were modelled with fuzzy logic modelling technique. In the developed RBMTF system, output parameters power (mW) was determined using inlet parameters T, t and bubble effect. Figs. 2-3 shows respectively comparison of experimental data of low bubble and high bubble effect with RBMTF for the variation of time with ΔT of power values for active and sedimentation mud ($\Delta T = 8-14^{\circ}\text{C}$; $t = 0-120$ s). From a comparison of the experimental results with the results of the fuzzy logic study, one can see that the results are quite compatible (Figs. 2-3).

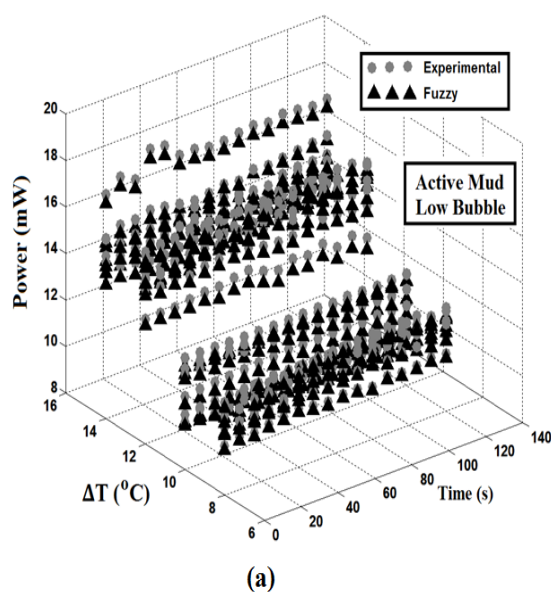


Fig 2. (a) Comparison of experimental data with RBMTF for the variation of time with ΔT of power values for active mud and low bubble.

2. (b) Comparison of experimental data with RBMTF for the variation of time with ΔT of power values for sedimentation mud and low bubble.

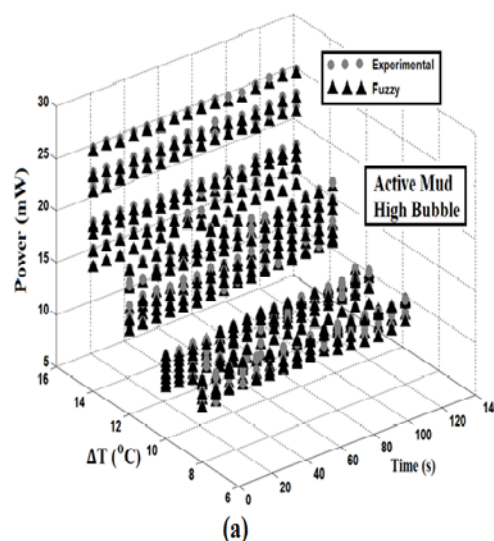
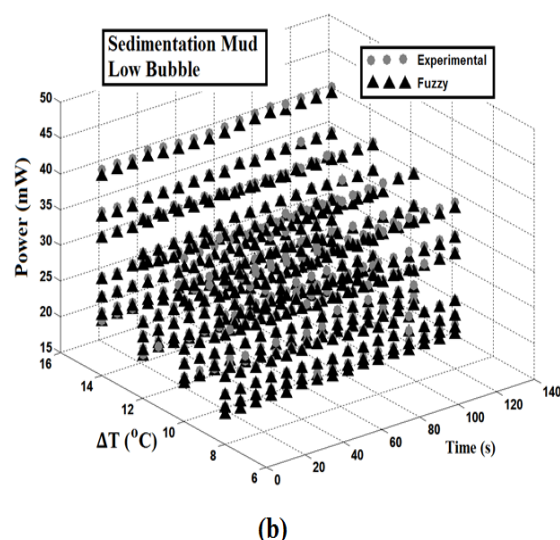
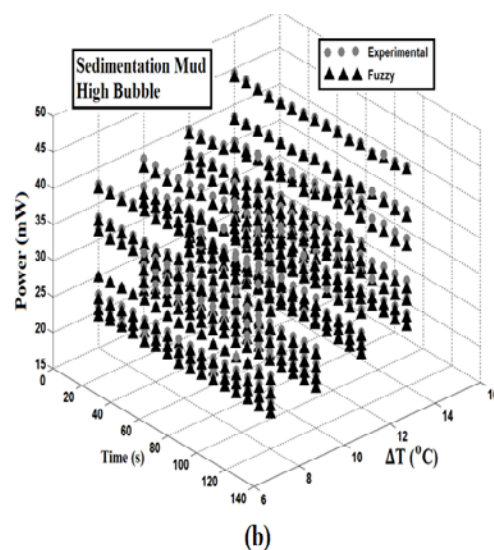


Fig. 3a) Comparison of experimental data with RBMTF for the variation of time with ΔT of power values for active mud and high bubble.

3b) Comparison of experimental data with RBMTF for the variation of time with ΔT of power values for sedimentation mud and high bubble.



These figures present that;

- For active mud and low bubble, the power values for $\Delta T=14$ °C is higher than other temperature differences. The power value for $\Delta T=14$ °C and $t=32$ s was 18.78 mW at most but $\Delta T=8$ °C and $t=32$ s was 10.41 mW (Fig.2a).
- For sedimentation mud and low bubble, the power values for $\Delta T=14$ °C is higher than other temperature differences. The power value for $\Delta T=14$ °C and $t=32$ s was 44.08 mW at most but $\Delta T=8$ °C and $t=32$ s was 19.75 mW (Fig.2b).
- For low bubble, same temperature and same time, sedimentation mud of power value is more than active mud power value. For $\Delta T=10$ °C and $t=80$ s, active mud power value was 11.1 mW, but sedimentation mud 23.55 mW (Fig.2(a-b)).
- Minimum power values were 10.11 mW and 19.6 mW for active and sedimentation mud respectively with low bubble effect (Fig.2(a-b)).
- For active mud and high bubble, the power values for $\Delta T=14$ °C is higher than other temperature differences. The power value for $\Delta T=14$ °C and $t=32$ s was 28.36 mW at most but $\Delta T=8$ °C and $t=32$ s was 10.88 mW (Fig.3a).
- For sedimentation mud and high bubble, the power values for $\Delta T=14$ °C is higher than other temperature differences. The power value for $\Delta T=14$ °C and $t=32$ s was 44.27 mW at most but $\Delta T=8$ °C and $t=32$ s was 20.1 mW (Fig.3b).
- For high bubble, same temperature and same time, sedimentation mud of power value is more than active mud power value. For $\Delta T=10$ °C and $t=80$ s, active mud power value was 13.29 mW, but sedimentation mud 32.87 mW (Fig.3(a-b)).
- Minimum power values were 10.26 mW and 19.86 mW for active and sedimentation mud respectively with high bubble effect (Fig.3(a-b)).

4. Conclusion

In this study, MFCs performances with active mud and sedimentation mud were experimentally investigated and modeled with fuzzy logic technique. In the experimental study, for sedimentation mud, high bubble and low bubble, the maximum power values determined as 45.5 mW and 43.9 mW; the minimum power values determined as 19.28 mW and 19.6 mW respectively. For active mud, high bubble and low bubble, the maximum power values determined as 28.29 mW and 18.87 mW; the minimum power values determined as 10.11 mW and 10.26 mW respectively. For sedimentation mud, low and high bubble power values nearly close. For $\Delta T=14$ °C and $t=32$ s, the power value was 43.9 mW for low bubble but for same time and ΔT , the power value was 45.5 mW for high bubble. For active mud, low and high bubble power values were more different than other. For $\Delta T=14$ °C and $t=24$ s, the power value was 18.45 mW for low bubble but for same time and ΔT , the power value was 28.36 mW for high bubble. Also, in this study, fuzzy logic modeling used to evaluate performance of MFCs. In the developed RBMTF system, outlet parameter power was determined using inlet parameters ΔT , t and bubble effect. The rules, which are used to detect the behavior of the fuzzy logic controller and the relationship between system's input and output, are determined. As a result of these rules, every value obtained from the experimental study is also determined by fuzzy logic too. The comparison between fuzzy logic and experimental data is done using statistical methods. The coefficient of multiple determination (R^2) is 98.79% for the all data. The actual values and fuzzy results indicated that fuzzy logic modelling can be successfully used for the specification MFCs performances.

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HYDROPHILIC NANOSTRUCTURE FORMATION ON THE TITANIUM SURFACE BY DIRECT LASER IRRADIATION

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Abstract: In the present paper, the model of nanostructure formation on solid surface by microsecond laser pulses melting the material is described. It is shown that typical size of surface nanostructure formed depends on laser wavelength, pulse energy, pulse repetition rate, and pulse duration. Within present work a series of 6 experiments devoted to direct laser nanostructuring of titanium (Ti) and copper (Cu) surfaces is carried out. Besides, the effects of nanoroughness on the contact and sliding angles on hydrophilic surfaces were studied theoretically and experimentally.

Keywords: NANOROUGHNESS OF SURFACE, CONTACT ANGLE, NANOSTRUCTURED HYDROPHILIC SURFACE, LASER IRRADIATION

1. Introduction

At the present time nanostructures are paid additional attention for being an extremely promising object regarding its application in different fields of science, technology and medicine. Surface nanostructuring leads to improvement of nanotribological ([1]), thermalphysic and thermodynamic ([2]), electron-emission ([3]) properties of materials, promotes rise of implants' biocompatibility ([4]-[6]) as well as leads to desired alteration of adhesive properties ([7]-[9]) and wettability ([10], [11]).

One of the most promising ways of periodic and/or nonperiodic nanostructure formation on implants' material surface, particularly on titanium surface, providing the implants with the desired adhesive and wettability properties, is direct laser nanostructuring (see [12], [13] and respective references given in these) which uses only a laser beam with no atomic-force microscope's ancillary needle or masks in order to form surface nanorelief. The advantage of this method consists in its simplicity and flexibility: (a) use of a single laser beam of a small size allows to achieve a high locality of exposure corresponding to the size (100x100 micrometer) of a separate laser spot; (b) use of software-programmable laser beam scanning on the implants' material surface with a high irradiation pulse repetition frequency allows to nanostructure sufficiently large surface areas within almost arbitrary boundaries with high spatial resolution.

This work, which in some sense is a continuation of the work [14], is devoted to formation of hydrophilic nanostructure on the surface of a ball-shaped titanium head of the human hip joint endoprosthesis using direct laser nanostructuring. The necessity of hydrophilicity property of the implant surface is due to the fact that the state of the surface of titanium implants plays a decisive role in cell-cell adhesion, because the interaction between a biological environment (hard and soft tissues, blood, body fluids and serum, etc.) and the implant occurs on its surface, and the biological response from the living tissue depends on a variety of surface properties, such as chemical composition, purity, texture and topography, surface energy, corrosion resistance, and the tendency to denaturalization of surrounding proteins. In this work, following the work [15], we will consider that a partially hydrophilic or hydrophobic surface with respect to any fluid is such a solid surface that for it the fluid gives a finite contact angle: if the contact angle θ between a drop of the liquid and the solid surface varies in the interval $\left(0, \frac{\pi}{2}\right)$, then this surface is called hydrophilic; if

$\theta \in \left[\frac{\pi}{2}, \frac{5 \cdot \pi}{6}\right]$, then the surface is called hydrophobic; if

$\theta \in \left(\frac{5 \cdot \pi}{6}, \pi\right]$, then the surface is classified as ultrahydrophobic;

with $\theta = 0$ and $\theta = \pi$ we have correspondingly complete wettability and complete nonwettability of the surface.

2. Scientific Basis: Mathematical Models and Design Formulas

2.1. Surface Energy, Surface Tension, and Surface Forces near the Phase Interfaces

Within representation of continuous medium, while analyzing two-phase systems, phase boundaries are interpreted as geometric surfaces. However, real phase boundaries are thin transition layers of a rather complicated structure. Molecules which form the transition layer interact with the molecules of both adjacent phases, that is why properties of transition layer differ from the properties of substance in the phases. This is the reason why during interpretation of phase boundaries there appear some phenomenological properties. Correct description of microsurface forces lies in the foundation of surface tension's and capillarity's interpretation both in the old approach of Clairaut and Laplace and in the new approach of Bakker ([16]-[18]), which is based on introducing the pressure tensor in the interphase area. Description of microsurface forces should begin with definition of interphase energy on the surface of phase boundary of phases solid-liquid (and also phases liquid-liquid, liquid-gas, solid-solid) and proceed with definition of surface forces in the interphase area. It is known ([19]) that if both phases are fluid (liquid-liquid, liquid-gas), then their phase boundary can be stretched or shrunk not affecting the thermodynamic equilibrium; if one phase is solid and the other is liquid or gaseous, then surface of their phase boundary can experience only elastic deformations, however some degree of freedom appears if the liquid is able to slide on the sufficiently smooth solid material (for example, like when quicksilver slides down the glass; water slides on the paraffin surface; blood or body fluids slide down the burnished surface of a titanium implant, etc.); if both phases are solid, then behaviour of the phase boundary is similar to the case solid-liquid, however the implementation of a real phase contact is possible only with atomic smoothness or requires plastic deformation, or prior melting, or evaporation and condensation with subsequent crystallization. Only in the case, when both phases are fluid, direct measurement of phase boundary tension is possible. In the case, when both phases are solid, direct measurement of phase boundary tension is achievable with some approximation if and only if in some temperature region yield point is lowered. In the case, when one phase is solid and the other is gaseous, direct measurement of phase boundary tension is impossible. The main mistakes made while measuring surface energy in the process of formation of a new surface are: (a)

omission of irreversible part of fracture work, which turns into heat or energy residual deformations; (b) omission of the fact that fresh (that is, just created) surfaces are in nonequilibrium state with higher energy – they appear to be covered by charge with density up to $3.5 \cdot 10^{-4} \text{ C} \cdot \text{m}^{-2}$, that consumes part of the fracture work. The special state of fresh surfaces is expressed not only by increased energy, but also by a higher chemical activity. Relaxation down to equilibrium state usually occurs for about ten minutes due to electron emission and surface conduction.

Formation of a new phase boundary is conjugate with consumption of work in order to move a part of molecules from the phases to the surface layer. In isothermal conditions the work of formation of phase surface's element dF is equal to increment of Helmholtz energy dU_F of the surface: $dU_F = \sigma \cdot dF$, where σ is specific Helmholtz energy of the phase boundary, which decreases as the temperature increases and at critical temperature $T_{c.t.}$ achieves the approximate value of zero (in steam-and-liquid systems $\sigma = 0$, and the difference between the phases disappears). The values of σ for the surface of a solid body on a border with a liquid are not identical to the corresponding coefficients of surface tension ([20]). Accurate theoretical formulas for calculation of liquids' surface tension coefficient do not exist. The main methodological difficulty of calculation of surface tension is the problem of ensuring solid surface purity, when it is in contact with a liquid, as well as liquid's purity. There are some methods of experimental calculation among which the most popular are ([21]): maximum gas bubble pressure method; capillary rise method; method of ring lifting; electromagnetic measurement methods; the drop weight method; hanging drop method; lying bubble or drop method. The simplest experimental method of determining the empirical dependence of phase boundary's specific Helmholtz energy on the temperature is the following relation obtained from

the theory of corresponding states ([22]): $\sigma = \sigma_0 \cdot \left(1 - \frac{T}{T_{c.t.}}\right)^{\frac{11}{9}}$,

where σ_0 is determined by the experiments carried out with one constant value of temperature. This formula has shown itself well working for liquids with homonuclear molecules, however it can be approximatively used also for the majority of other liquids. For calculations of water's σ it is recommended to use the following

interpolation formula: $\sigma = 0.235 \left(1 - \frac{T}{T_{c.t.}}\right)^{1.256} \left(1 - 0.625 \frac{T_{c.t.} - T}{T_{c.t.}}\right)$.

2.2. Wetting Process

In the introduction we mentioned (following the work ([15])) the contact angle of wetting θ between a solid surface and a tangent to the phase boundary gas-liquid. From the minimality condition of surface's Helmholtz energy ([23], [24]) one can obtain the following relation known as Young's law:

$\theta = \arccosine\left(\frac{\sigma_{solid,gas} - \sigma_{solid,liquid}}{\sigma}\right)$. It is important to note that the

contact angle is very sensitive to such difficult-to-control factors as roughness of a solid surface or presence of foreign impurity on the solid surface or in the liquid, particularly if this impurity is surface-active, which, concentrating on the thermodynamic phase boundary, cause surface tension lowering: for instance, R-OH alcohols; R-COH aldehydes; R-COOH carboxylic acids; CH₃-, C₂H₅-, C₁₇H₃₅-, etc. hydrocarbon radicals; COH and COOH functional groups; oleic acid C₁₇H₃₃COOH; stearic acid sodium C₁₇H₃₅COONa; etc. Rise in the roughness of the solid surface increases its wettability, that is, decreases the value of θ . For some solid bodies participating in the phase solid-liquid in a certain interval of temperature holds a dependence of the contact angle θ on the temperature ([25]). As it is shown in [25], almost always a growth of temperature on a hydrophilic surface leads to

improvement of wettability, that is, to diminution of the angle θ , but on hydrophobic surfaces – to worsening of wettability, that is, to growth of the angle θ . Also it is important to note (especially, if we are speaking about implants) that the contact angle of wetting θ depends also on hysteresis of wetting – on the direction of wetting a solid body surface by a liquid, that is, on the fact, whether the liquid is flowing on the surface or down it.

2.3. The Phase Separation Surface's Equilibrium, and Axisymmetric Equilibrium Separation Surfaces of Phases

If the liquid rests relative to the coordinate system related to Earth, then in hydromechanics this rest is called absolute rest; if the liquid rests relative to the coordinate system which moves with uniform acceleration relative to Earth, then this rest is called relative rest. For both absolute rest and relative rest Euler's

equations in the vector form hold: $\vec{F} - \frac{1}{\rho} \cdot \nabla p = 0$, where $\vec{F}$ is

mass forces density vector, which, in the case of relative rest, includes inertial forces; ρ is liquid density; p is liquid pressure.

Due to the fact that mass forces have potential in the majority of cases, one can write $\vec{F} = -\nabla\Phi$, where Φ is a force function. Consequently, Euler's equation turns into equation

$\nabla\Phi + \frac{1}{\rho} \cdot \nabla p = 0$, whose general integral for the cases, when

$\rho = \rho(p)$, is the formula $\Phi + \Upsilon = const$, called the equation of

hydrostatics, where $\Upsilon = \int \frac{dp}{\rho}$ denotes pressure function. It should

be noted that, if the liquid is a heavy compressible liquid, then out of all mass forces only gravitational force affects it, so the general integral looks like $\Phi = g \cdot z + const$, where z denotes the coordinate which is counted vertically up. For a heavy compressible liquid the general integral of Euler's equation has the form

$z + \frac{p}{g \cdot \rho} = const$, and this formula represents hydrostatic

distribution of pressure. When a gas-liquid system is in the equilibrium state, then in each contacting phase, firstly, the equations of hydrostatics hold and, secondly, for every point on phase boundary defined by a position vector $\vec{r}$ Laplace formula

$p_1 - p_2 = 2 \cdot \sigma \cdot H(\vec{r})$ is true, which means that on the boundary

between two fluid phases the surface tension causes a pressure jump in the contacting phases, which is proportional to average curvature H of the phase boundary. From these two relations (equation of hydrostatics and Laplace formula) one can deduce the main differential equation of hydrostatic equilibrium

$2 \cdot \sigma \cdot H(\vec{r}) = (\rho_{liquid} - \rho_{gas}) \cdot \Phi(\vec{r}) + const$, whose general integral

determines the shape of phase boundary. In the most practically important axial-symmetric problems on liquid there are: homogeneous gravitational field with intensity g , directed along vertical axis OZ ; centrifugal force field caused by uniform rotation of the gas-liquid system around the same axis OZ with angular velocity ω . In this case, the potential of mass forces has the form

$\Phi = g \cdot z - \frac{1}{2} \cdot \omega^2 \cdot d^2$, where $d = \sqrt{x^2 + y^2}$ is the distance to the

rotation axis. When the system rests, potential of mass forces is determined by the formula $\Phi = g \cdot z$, but the main equation of hydrostatic equilibrium has the form:

$2 \cdot \sigma \cdot H(z) = \delta \cdot g \cdot (\rho_{liquid} - \rho_{gas}) \cdot z + 2 \cdot \sigma \cdot H(0)$, where the term $2 \cdot \sigma \cdot H(0)$ represents the pressure jump on some "zero" level;

$\delta = +1$ in the case, when the vertical axis OZ is pointed up (and the gravitational field is pointed down), and $\delta = -1$ in the case, when the vertical axis OZ is pointed down. For a resting system

with a characteristic size $L_{ch.d.}$ it is possible to use the main equation of hydrostatic equilibrium in order to obtain the scale of gravitational forces $f_{grav} \propto g \cdot (\rho_{liquid} - \rho_{gas}) \cdot L_{ch.d.}$ and the scale of surface tension forces $f_{s.t.} \propto \frac{\sigma}{L_{ch.d.}}$. Then Bond number Bo , which

is the criterion of similarity in hydrodynamics and determines relation between external forces (usually, gravity) and surface tension forces has the following form:

$$Bo = \frac{f_{grav}}{f_{s.t.}} = g \cdot (\rho_{liquid} - \rho_{gas}) \cdot \frac{L_{ch.d.}^2}{\sigma}. \quad \text{The condition } Bo = 1$$

determines linear size of the region, where gravitational forces and surface tension forces are equal: $L_{lin.d.} = \sqrt{\frac{\sigma}{g \cdot (\rho_{liquid} - \rho_{gas})}}$. The

quantity $L_{lin.d.}$ is called capillary constant. For the majority of liquids with $p \leq p_{c.t.}$ ($p_{c.t.}$ is critical pressure), that is, in Earth conditions, the value of capillary constant varies within 1–3 mm. Obviously, if one divides the equation of hydrostatic equilibrium $2 \cdot \sigma \cdot H(z) = \delta \cdot g \cdot (\rho_{liquid} - \rho_{gas}) \cdot z + 2 \cdot \sigma \cdot H(0)$ by the quantity $\sqrt{\sigma \cdot g \cdot (\rho_{liquid} - \rho_{gas})}$, then it turns into the following

dimensionless form: $2 \cdot \tilde{H}(\tilde{z}) = \delta \cdot \tilde{z} + C$, where $\tilde{H} = L_{lin.d.} \cdot H$, $\tilde{z} = \frac{z}{L_{lin.d.}}$, $C = 2 \cdot H(0) \cdot L_{lin.d.}$.

2.4. Melting Process

At sufficient energy density, duration and order of a laser pulse melting of solid body's surface occurs – in our case, of ball-shaped titanium head of the human hip joint endoprosthesis. When the laser pulse irradiation stops, the process of cooling the processed surface starts and is carried out by the means of heat removal deep into the solid phase and subsequent solidification of the surface layer. It is supposed that the power of laser irradiation is such that phase transition solid-liquid occurs. Then, with appropriate approximation, temperature fields in the liquid $T_{liquid}(x, t)$ and solid $T_{solid}(x, t)$ phases can be described by following boundary value problem ([13], [26], [27]):

$$\frac{\partial T_{liquid}(x, t)}{\partial t} = a_{liquid} \cdot \frac{\partial^2 T_{liquid}(x, t)}{\partial x^2}, \quad 0 < x < y(t), \quad (1)$$

$$\frac{\partial T_{solid}(x, t)}{\partial t} = a_{solid} \cdot \frac{\partial^2 T_{solid}(x, t)}{\partial x^2}, \quad y(t) < x < \infty, \quad (2)$$

$$T_{solid}(x, t)|_{t=0} = T_{solid}(x, t)|_{x=\infty} = T_0, \quad (3)$$

$$\frac{\partial Q(t)}{\partial t} + \lambda_{liquid} \cdot \frac{\partial T_{liquid}(x, t)}{\partial x} \bigg|_{x=0} = 0, \quad (4)$$

$$T_{liquid}(x, t)|_{x=y(t)} = T_{solid}(x, t)|_{x=y(t)} = T_1, \quad (5)$$

$$\lambda_{liquid} \frac{\partial T_{liquid}(x, t)}{\partial x} \bigg|_{x=y(t)} = H \rho y'(t) + \lambda_{solid} \frac{\partial T_{solid}(x, t)}{\partial x} \bigg|_{x=y(t)}. \quad (6)$$

where $y(t)$ is the moving boundary of the phase transition; $Q(t)$ is the absorbed energy per surface unit for the time $t \leq \tau$, where τ denotes the duration of a laser pulse; $a = \frac{\lambda}{c \cdot \rho}$ is thermal diffusivity, where λ , c and ρ denote correspondingly thermal

conductivity, specific heat and density of a metal ($a_{solid}, \lambda_{solid}, c_{solid}, \rho_{solid}$) or liquid ($a_{liquid}, \lambda_{liquid}, c_{liquid}, \rho_{liquid}$); T_0 and T_1 denote correspondingly initial temperature of the solid body and the temperature of the phase transition; H is latent melting heat, which is absorbed on the moving phase boundary. Supposing that the temperature of the metal surface processed by laser pulse achieves phase transition point during the time $t_0 \leq \tau$ and the temperature of liquid phase varies slightly during further process $t_0 < t < \tau$, we can replace the boundary condition (4) by the following more simple condition:

$$T_{liquid}(x, t)|_{x=0} = T_2 = T_{liquid}(x, \tau)|_{x=0} > T_1, \quad (7)$$

where T_2 is a temperature of molten metal on the surface that can be defined by heat balance equation. Combining (1)-(3), (5) and (7) we can write that

$$T_2 = T_1 + \frac{\operatorname{erf}\left(\frac{\beta}{\sqrt{2 \cdot a_{liquid}}}\right)}{2 \cdot c_{liquid} \cdot \rho \cdot \sqrt{a_{liquid}} \cdot \left(1 - e^{-\frac{\beta^2}{2 \cdot a_{liquid}}}\right) \cdot \operatorname{erfc}\left(\frac{\beta}{\sqrt{2 \cdot a_{solid}}}\right)} \times \\ \times \left\{ \left(\sqrt{\frac{\pi}{\tau}} \cdot Q(\tau) - \sqrt{2 \cdot \pi} \cdot H \cdot \rho_{solid} \cdot \beta \right) \cdot \operatorname{erfc}\left(\frac{\beta}{\sqrt{2 \cdot a_{solid}}}\right) - \right. \\ \left. - 2 \cdot c_{solid} \cdot \rho_{solid} \cdot (T_1 - T_0) \right\}, \quad (8)$$

where $Q(\tau) = H \cdot \rho \cdot y(\tau) + \int_0^{y(\tau)} c_{solid} \cdot \rho_{solid} \cdot (T_1 - T_0) dx$

$$+ \int_0^{y(\tau)} c_{liquid} \cdot \rho \cdot (T_{liquid} - T_1) dx + \int_{y(\tau)}^{\infty} c_{solid} \cdot \rho_{solid} \cdot (T_{solid} - T_0) dx; \quad (9)$$

parameter β can be found from the following transcendental equation:

$$\frac{2 \cdot \sqrt{\frac{a}{\pi}} \cdot c \cdot \rho \cdot (T_1 - T_0)}{\operatorname{erfc}\left(\frac{\beta}{\sqrt{2 \cdot a}}\right)} = \sqrt{2} \cdot H \cdot \rho \cdot \beta \cdot \left(e^{\frac{\beta^2}{2 \cdot a}} - 2 \right) + \frac{Q(\tau)}{\tau}. \quad (10)$$

The formulas (8)-(10) allow us to calculate melting depth of different solid materials irradiated by laser pulses of various duration and energy.

As it has already been mentioned above, under the influence of laser irradiation high temperature stress occurs in the metals. Deformation process in these conditions is followed by residual deformation, whose appearance is related to nonelastic effects and reorganization of crystal's defect structure. Stress' relaxation can have heterogeneous character due to formation of new structure zones called relaxation zones ([32]) in the old excited structure. Depending on the state of the system, on the conditions of external influence, on the degree of process development it may occur that relaxation zones can be centers of a new phase, groups of dislocations and disclinations, microcracks, clusters of atoms and vacancies forming clusters, micropore, dislocation loops, etc. One can imagine the deforming as three simultaneously coexistent phases: relaxation field determined by the parameter $\varphi_{i,j}(r, t)$, stress field $\sigma_{i,j}(r, t)$ corresponding to external load and relaxation zones with concentration $n(r, t)$. Temporary dependence

$\varphi_{i,j}(r,t)$, $\sigma_{i,j}(r,t)$ and $n(r,t)$ is defined by the following system of nonlinear differential equations:

$$\begin{cases} \dot{\varphi}_{i,j} = -\kappa \cdot \varphi_{i,j} + g_1 \cdot n, \\ \dot{n} = -\gamma \cdot n + \frac{\varphi_{i,j} \cdot \sigma_{i,j}}{g_2}, \\ \dot{\sigma}_{i,j} = \nu \cdot (\sigma_{i,k} - \sigma_0) - g_3 \cdot \varphi_{i,j} \cdot n, \end{cases} \quad (11)$$

where parameters κ , γ , ν , g_i ($i=1,3$) are material constant; quantity σ_0 is determined by the applied external loads and corresponds to the residual stress set as the result of relaxation.

In the system (11) the term $-\kappa \cdot \varphi_{i,k}$ is the decay of the relaxation process; the term $-\gamma \cdot n$ describes disintegration of the formed relaxation zones; the term $\nu \cdot (\sigma_{i,k} - \sigma_0)$ describes the stress relaxation in linear approximation, when their interference is absent; the term $g_1 \cdot n$ is related to relaxation field generation due to

formation of relaxation zones; the term $\frac{\varphi_{i,k} \cdot \sigma_{i,k}}{g_2}$ takes into account

the influence of the relaxation field $\varphi_{i,j}(r,t)$ and stress field $\sigma_{i,j}(r,t)$ on the generation of relaxation zones; the term $g_3 \cdot \varphi_{i,j} \cdot n$ is caused by the influence of the relaxation field and relaxation zones on the speed of stress relaxation. As the speed of alteration of the relaxation field is much lower than the speed of the processes atomic relaxation described by the constants γ and ν , in (7) one can use adiabatic elimination of variables. Taking into account possible spatial fluctuations whose role grows as temperature and external loads grow, we get the following kinetic equation for relaxation parameter:

$$\varphi_{i,j} = A\varphi_{i,j} - B\varphi_{i,j}^3 + D\Delta\varphi_{i,j}, \quad (12)$$

where $A = \frac{g_1}{g_2 \cdot \gamma} \left(\sigma_0 - \frac{g_2 \cdot \gamma}{g_1} \cdot \kappa \right)$; $B = \frac{g_1 \cdot g_3}{g_2^2} \cdot \frac{\sigma_0}{\gamma^2 \cdot \nu}$; D is

diffusion coefficient of atoms in a warmed-up zone. If we take into account diffusion's dispersion, then equation (12) will turn into Ginzburg-Landau generalized equation ([33], [34]). For

$\sigma_0 < \sigma_c = \frac{g_2 \cdot \gamma}{g_1} \cdot \kappa$ equation (12) has one stable solution

$\varphi_{i,j}(r,t) = 0$; if exceeding of the critical value $\sigma_0 > \sigma_c$ occurs, new coherent states of the system are realized with spatial periodicity, whose period can be calculated using the formula

$P = \frac{\sigma_0 - \sigma_c}{2 \cdot \pi \cdot \sigma_0} \cdot \sqrt{\frac{3 \cdot D}{8 \cdot \nu}}$. Using the kinetic equation from the theory of

surface nucleation ([2], [28]-[30]) as well as variational principle for the main laws of thermal conduction, one can obtain ([31]) the following closed formula for characteristic size-radius of a crystalline phase nucleus in a supercooled liquid:

$$r(t) = \nu_0 \cdot d \cdot e^{-\frac{U}{k \cdot T_1}} \cdot \frac{k \cdot T_1^2}{U \cdot \varepsilon} \cdot \left(\frac{h}{U+h} - e^{-\frac{U \cdot \varepsilon \cdot t}{k \cdot T_1^2}} + \frac{U}{U+h} \cdot e^{-\frac{(U+h) \cdot \varepsilon \cdot t}{k \cdot T_1^2}} \right), \quad (11)$$

where ν_0 is Debye oscillation frequency of atoms in a supercooled liquid; U is the activation energy for atom movement; $k \cdot T$ is thermal energy; d is characteristic size for a single atom; h is the heat of phase transformation for one atom; ε is the average speed of melt cooling. Using the formula (11) one can precisely estimate characteristic size-radius of a crystalline phase nucleus, that is, the

size of nanostructures appearing on the surface of the processing solid body, while it is melting under laser pulse irradiation.

3. Experimental Facility, Experiments and Results

Within present work we have carried out a series of 6 experiments devoted to direct laser nanostructuring of titanium (Ti) and copper (Cu) surface. All the processed samples had the same sizes: $L \times W \times H = 5 \times 3 \times 0.1$ mm. Samples' surfaces had 14th surface finish class. Samples were placed in a laser facility chamber Nd³⁺:YAG crystal and were irradiated in a motionless laser beam. For a detailed analysis of the irradiated samples' profiles we used a desktop scanning electron microscope Hitachi TM3030 with low vacuum regime, which allows to carry out the experiments without sample preparation and to investigate samples without prior metal deposition; controlled by a simple and understandable interface with the functions of automatic focus, contrast and brightness setting; equipped with two detectors – of secondary and reflected electrons, – owing to which it is possible to get comprehensive information about the surface of the investigated samples. Laser facility Nd³⁺:YAG crystal, which was used in order to carry out a series of experiments devoted to direct laser nanostructuring of surfaces of 4 titanium and 2 copper samples, has the following capabilities: laser wavelength: 532 nm; maximum pulse energy: 0.15 J; pulse repetition rate: 10 Hz; initial pulse duration: 5÷9 ns; pulse duration: 5÷400 μs. After repeated irradiation with one beam of microsecond Nd³⁺:YAG crystal-laser formation of nanosized structures on the copper and titanium surfaces was noticed. Laser irradiation intensity was maximal in the center of the irradiation spot and was going down closer to its periphery. After repeated pulse action on one surface patch a deep crater appeared in the spot's center. However, on the periphery, where the laser irradiation intensity was lower, one could notice only some surface melting. Using SEM-analysis (that is, using scanning electron microscopy with X-ray spectrometry microanalysis) no submicrometer structures were detected in the central high-intensity part of the spot. However, formation of nanorelief was detected in the peripheral part of the irradiation zone. For all 6 samples we detected roughness of characteristic size along the surface on the surface in the peripheral low-intensity region of the spot as well as small-scale roughness in the form of saliences put over the surface. Round shape of the obtained nanoreliefs implies the surface being molten by the laser irradiation and subsequent crystallization with formation of the above mentioned submicrometer structures. Taking into account the possibility of slight material melting, we can consider a surface under thermal flow of pulsed laser irradiation which causes phase transition solid-liquid.

3.1. Experiment 1

In this experiment copper foil was taken as a sample, and for its laser processing the following characteristics of microsecond laser facility Nd³⁺:YAG crystal were chosen: laser wavelength (LW): 532 nm; pulse energy (PE): 0.14 J; pulse repetition rate (PRR): 10 Hz; pulse duration (PD): 130 μs. Results of a single pulse action on this sample are shown on the Fig.1. The obtained nanostructured surface has a good hydrophilic property: water was used as the liquid.

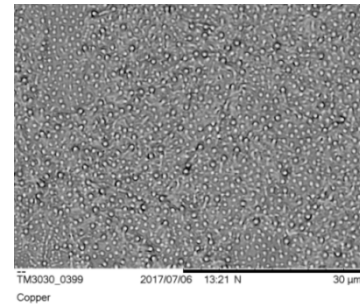


Fig. 1 Nanostructured copper surface (one-time processing) with a good hydrophilic property. PE=0.14 J; PD=130 μs.

3.2. Experiment 2

In this experiment copper foil was again taken as a sample, and for its laser processing the following characteristics of microsecond laser facility Nd³⁺:YAG crystal were chosen: laser wavelength: 532 nm; pulse energy: 0.14 J; pulse repetition rate: 10 Hz; pulse duration: 130 μ s. Results of a twofold pulse action on this sample are shown on the Fig.2. The obtained nanostructured surface has a much worse hydrophilic property: water was used as the liquid.

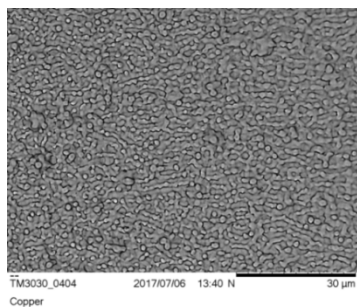


Fig. 2 Nanostructured copper surface (twofold processing) with a bad hydrophilic property. PE=0.14 J; PD=130 μ s.

3.3. Experiment 3

In this experiment titanium foil was taken as a sample, and for its laser processing the following characteristics of microsecond laser facility Nd³⁺:YAG crystal were chosen: laser wavelength: 532 nm; pulse energy: 0.15 J; pulse repetition rate: 10 Hz; pulse duration: 100 μ s. Results of a single pulse action on this sample are shown on the Fig.3. The obtained nanostructured surface has a very good hydrophilic property: both water and physiological solution 0.9% NaCl were used as the liquid.

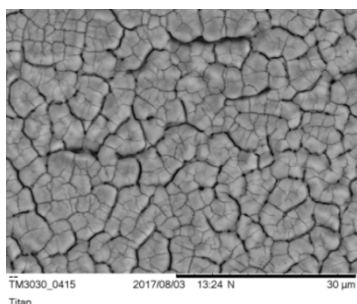


Fig. 3 Nanostructured titanium surface (one-time processing) with a very good hydrophilic property. PE=0.15 J; PD=100 μ s.

3.4. Experiment 4

In this experiment titanium foil was again taken as a sample, and for its laser processing the following characteristics of microsecond laser facility Nd³⁺:YAG crystal were chosen: laser wavelength: 532 nm; pulse energy: 0.15 J; pulse repetition rate: 10 Hz; pulse duration: 130 μ s. Results of a single pulse action on this sample are shown on the Fig.4. The obtained nanostructured surface has a good hydrophilic property, however it is slightly worse, than in the results of the third experiment: both water and physiological solution 0.9% NaCl were used as the liquid.

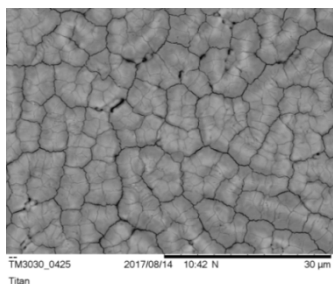


Fig. 4 Nanostructured titanium surface (one-time processing) with a good hydrophilic property. PE=0.15 J; PD=130 μ s.

3.4. Experiment 5

In this experiment titanium foil was again taken as a sample, and for its laser processing the following characteristics of microsecond laser facility Nd³⁺:YAG crystal were chosen: laser wavelength: 532 nm; pulse energy: 0.15 J; pulse repetition rate: 10 Hz; pulse duration: 85 μ s. The processing was implemented by the stripes with use of a lens for focusing of laser beam. Results of a single pulse action on this sample are shown on the Fig.5. The obtained nanostructured surface has the following hydrophilic property: the liquid (water and physiological solution 0.9% NaCl) flows only in one direction.

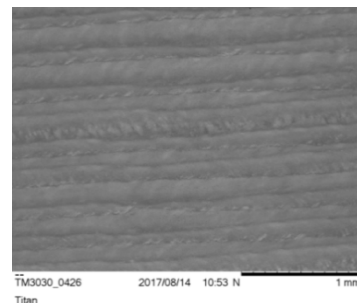


Fig. 5 Nanostructured titanium surface (one-time processing with a lens for focusing of a laser beam): the liquid flows only in one direction. PE=0.15 J; PD=85 μ s.

3.4. Experiment 6

In this experiment titanium foil was again taken as a sample, and for its laser processing the following characteristics of microsecond laser facility Nd³⁺:YAG crystal were chosen: laser wavelength: 532 nm; pulse energy: 0.15 J; pulse repetition rate: 10 Hz; pulse duration: 300 μ s. Results of a single pulse action on this sample are shown on the Fig.6. The obtained nanostructured surface has a very good hydrophilic property: both water and physiological solution 0.9% NaCl were used as the liquid.

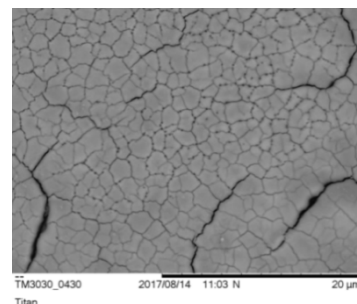


Fig. 6 Nanostructured titanium surface (one-time processing) with a very good hydrophilic property. PE=0.15 J; PD=300 μ s.

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STRUCTURE, MECHANICAL PROPERTIES AND CORROSION RESISTANCE OF MAGNESIUM ALLOY WE43 AFTER EQUAL-CHANNEL ANGULAR PRESSING

СТРУКТУРА, МЕХАНИЧЕСКИЕ СВОЙСТВА И КОРРОЗИОННАЯ СТОЙКОСТЬ МАГНИЕВОГО СПЛАВА WE43 ПОСЛЕ РАВНОКАНАЛЬНОГО УГЛОВОГО ПРЕССОВАНИЯ

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Abstract: ECAP was conducted using route Bc with an angle of 120° between the die channels and a stepwise decrease of temperature from the initial 425 °C to 300 °C at the final, 12th pass. The cumulative equivalent strain the ECAP billets underwent was about 7.8. The structure examination showed that ultrafine-grained structure with the grain size of 0.69 – 1 μm was formed during ECAP process. In addition, particles of the phase Mg₁₂Nd with an average size of 0.45 μm were formed. The refinement of the microstructure resulted in an improvement of the mechanical properties of the alloy. After ECAP, the strength characteristics of the alloy increased to the levels of ultimate tensile strength of 300 and yield strength of 260 MPa to be compared to those for the initial state (220 MPa and 150 MPa, respectively). At the same time, the ductility increased to 13.2 %, which compares favourably with the initial value of 10.5 %. The ECAP process does not affect the resistance to electrochemical corrosion. The rate of chemical corrosion was found to be reduced owing to the ECAP processing. **KEYWORDS:** MAGNESIUM ALLOYS, SEVERE PLASTIC DEFORMATION, EQUAL CHANNEL ANGULAR PRESSING, ULTRAFINE GRAINED STRUCTURE, MECHANICAL PROPERTIES, CORROSION RESISTANCE

1. Introduction

The magnesium alloy WE43 (Mg-4%Y-3%(Nd+RE)-0.5%Zr) is a high-strength casting alloy, which finds successful applications in the aerospace and automotive industries. It is also a promising material for medical application due to its good biocompatibility [1, 2]. However, modification of the alloy is necessary for the successful use of the alloy by improving the strength characteristics, as well as corrosion resistance. There are a number of works devoted to severe plastic deformation (SPD) of WE43 alloy [3-14], including equal-channel angular pressing (ECAP) [15-17]. They demonstrated that the use of SPD process allows to refine the grain up to 30 nm [14], resulting in substantial hardening of the alloy. In addition, it was shown in [18, 19] that ultrafine-grained (UFG) and nano structure makes it possible to improve the corrosion resistance of magnesium alloys. Based on this, it can be concluded that the SPD is a promising treatment for increasing both strength and corrosion resistance. Therefore, the purpose of this work was to study the structure, mechanical properties and corrosion resistance of the magnesium WE43 alloy after equal-channel angular pressing.

2. Materials and Methods

In this paper we used a commercial WE43 (Mg-4%Y-3%(Nd+RE)-0.5%Zr, wt.%) alloy. As an initial state, the ingot was homogenized at 525 °C for 8 hours. The samples of cylindrical shape with a diameter of 10 mm and a height of 80 mm were cut from the obtained rod for ECAP. Route Bc ECAP was conducted using a die with an angle of 120° between the channels for two regimes with different temperatures of beginning and finishing of treatment. For regime 1, the deformation temperature was reduced from 400 °C to 350 °C in increments of 50 °C. The alloy was deformed into 6 passes at each temperature. In case of the second regime the temperature was reduced from 425 °C to 300 °C in increments of 25 °C. The alloy was deformed into 2 passes at each temperature. The total number of passes was 12 for both regimes (Fig. 1), which corresponds to a true strain equal of 7.8. The microstructure was examined using an optical microscope Reichert MeF and a transmission electron microscope (TEM) JEM 1400 operating at 120 kV. Samples for TEM analysis after ECAP were cut in the longitudinal direction and then thinned to 150 μm. Further, the foil was subjected to electrolytic etching in an electrolyte consisting of 75% CH₃COOH and 25% HNO₃ at -35 °C using a Struers TenuPol-5 jet grinder.

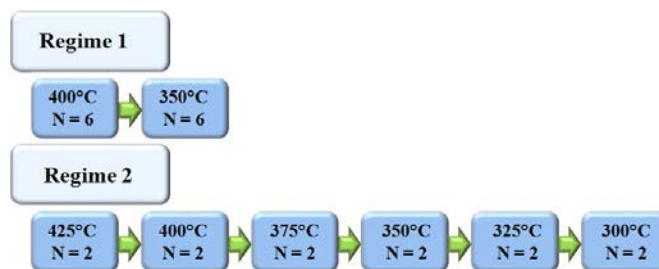


Fig. 1. Deformation scheme of the alloy during ECAP process.

The evaluation of mechanical properties was carried out by performing uniaxial tension tests at room temperature. The tests were carried out on an Instron1096 test machine at a strain rate of 1.5 mm/min on samples with a working length l equal to 15 mm and a working diameter d equal to 3 mm.

Corrosion resistance was evaluated by the potentiodynamic polarization, weight loss and hydrogen evolution methods in a 0.9% NaCl solution (pH = 7). All electrochemical tests were carried by VMP potentiostat controlled by EC-Lab software (Bio-logic). The setups were using PAR flat cell which has a "three electrode configurations" (working electrode, saturated calomel reference electrode and Pt-mesh counter electrode). Previously, the material was subjected to mechanical grinding on abrasive paper with gradually decreasing granularity (from P800 to P2500). Scanning was performed with a scan rate equal to 1 mV per second in the range from 100 mV below the open circuit potential (OCP) to -1000 mV. The dwell time prior to the commencement of the scan, which is necessary that the surface to form an electrical double layer (EDL) and associated redistribution of species in the electrolyte was 10 minutes [20]. The number of scan repetitions was 5 for each test sample. Before each scan, the sample was repolished. The weight loss and hydrogen evolution tests were carried out in a 0.9% NaCl solution (pH = 7) at room temperature and 37 °C [20, 21]. The test duration was 1 day for both methods of corrosion resistance assessment. Samples after weight loss tests were washed in a cleaning solution consisting of 200g Cr₂O₃, 10g AgNO₃, 20g Ba(NO₃)₂ and distilled water to make 1 liter of solution for 1 minute to remove corrosion products, and then weighed on an electronic balance GR 200. Calculation of the corrosion rate was performed according to ASTM G1 (Standard Practice for Preparing, Cleaning, and Evaluation Corrosion Test Specimens).

3. Results and Discussion

There are equiaxed grains of a supersaturated magnesium solid solution of 70 μm in the alloy after homogenization at 525 $^{\circ}\text{C}$ and subsequent cooling in air. An ultrafine-grained structure with the average grain size of $1.00 \pm 0.14 \mu\text{m}$ for regime 1 and $0.69 \pm 0.13 \mu\text{m}$ for regime 2 is formed during the ECAP (Fig. 1). The occurrence of high-angle boundaries is confirmed by ring-like electron diffraction patterns with a number of point reflexes. Furthermore, the particles of the equilibrium Mg_{12}Nd phase of $0.41 \pm 0.18 \mu\text{m}$ and $0.45 \pm 0.18 \mu\text{m}$ in size were observed in both cases (for regimes 1 and 2, respectively). It was shown in [14] that the HPT process accelerates the decomposition of a supersaturated magnesium solid solution, by forming a larger number of defects that act as a substrate for nucleation of particles. It should be noted that a similar effect appeared in case of ECAP, since the decomposition of the supersaturated magnesium solid solution occurred already during deformation and heating process of the treatment. It is also worth noting that we observed the deformation twins in the structure after ECAP in case regime 2 (Fig. 2 d). The smaller grain and the existence of twins in the structure of the alloy after deformation by regime 2 can be probably caused by the lesser end temperature of deformation compared with regime 1.

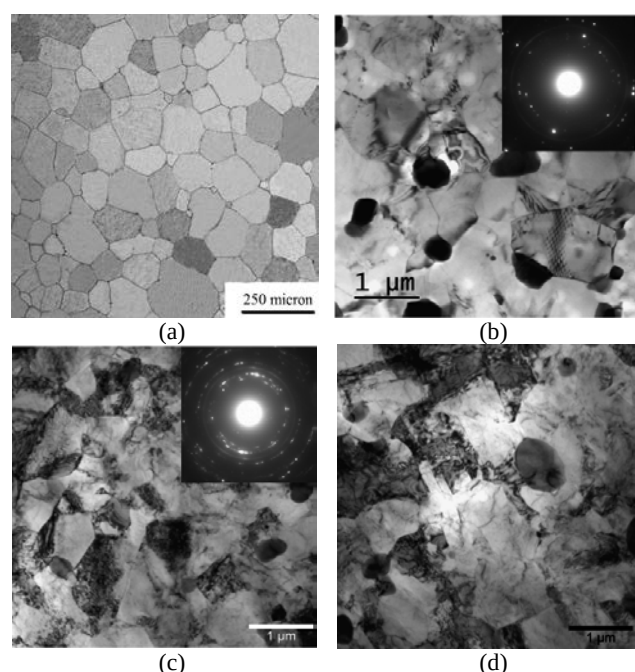


Fig. 2. Microstructure of WE43 alloy in initial state (a) and after ECAP for regime 1 (b) and regime 2 (c, d).

The refinement of the structure during ECAP process leads to strengthening of the WE43 alloy. For regime 1, the values of the yield strength increases up to $\text{YS} = 180 \text{ MPa}$ and the ultimate tensile strength – up to $\text{UTS} = 250 \text{ MPa}$ compared with the initial state (150 MPa and 220 MPa, respectively) with a slight decrease in ductility from 10.5 to 7%. However, the increase in ductility up to 13.2% occurs along with an increase in the ultimate tensile strength and the yield strength up to 300 and 260 MPa, respectively, for regime 2 (Tab. 1). The high level of strength in case of regime 2 can apparently be explained by a more dispersed structure and also by the existence of deformation twins in the structure.

Table 1. Mechanical properties of WE43 alloy in the initial state and after ECAP treatment

Treatment	UTS, MPa	YS, MPa	EL, %
Initial state	220	150	10.5
ECAP Regime 1	250	180	7.0
ECAP Regime 2	300	260	13.2

Fig. 3 and Table 2 demonstrate the results of potential dynamic polarization tests. The obtained results showed that deformation by ECAP practically does not influence on the resistance to electrochemical corrosion of WE43 alloy. For regime 1, the potential of corrosion remains equal within the error to the corrosion potential in initial state ($-1622 \pm 19 \text{ mV}$ and $-1630 \pm 34 \text{ mV}$, respectively). In case of regime 2, a slight decrease occurs to the value of $-1686 \pm 8 \text{ mV}$. The values of the corrosion current density, corresponding rate of corrosion, are the same within experimental error for all three states of the alloy ($21.30 \pm 4.50 \mu\text{A}/\text{cm}^2$, $16.18 \pm 3.14 \mu\text{A}/\text{cm}^2$ and $21.81 \pm 6.50 \mu\text{A}/\text{cm}^2$ for initial state, ECAP regime 1 and ECAP regime 2, respectively).

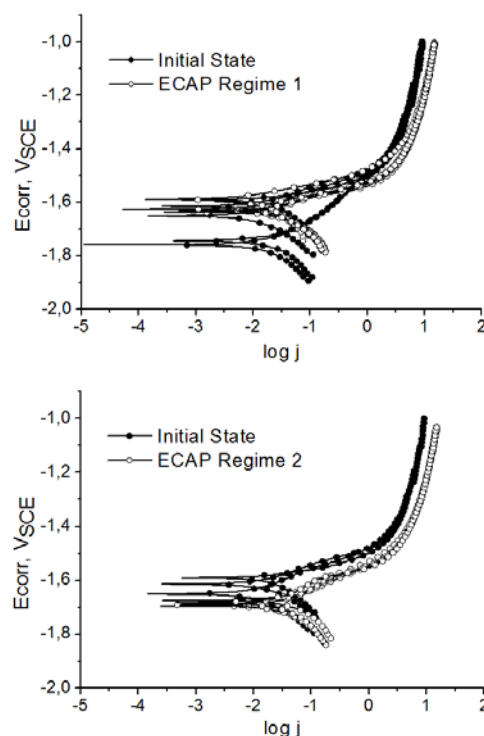


Fig. 3. Polarization curves (potential E in volts with respect to a saturated calomel electrode (SCE) vs. current j) for the WE43 alloy in the initial state and after ECAP for regime 1 (a) and regime 2 (b).

Table 2. Results of PDP tests of the WE43 alloy in the initial state and after ECAP treatment

Treatment	E_{corr} , mV_{SCE}	j_{corr} , $\mu\text{A}/\text{cm}^2$
Initial state	-1630 ± 34	21.30 ± 4.50
ECAP Regime 1	-1622 ± 19	16.18 ± 3.14
ECAP Regime 2	-1686 ± 8	21.81 ± 6.50

At the same time, the study of resistance to chemical corrosion revealed an improvement in corrosion resistance after ECAP. Fig. 4 shows the results of measuring the corrosion rate by weight loss (WL) and hydrogen evolution (HE) methods at room temperature and 37 $^{\circ}\text{C}$. It can be seen that the corrosion rate after ECAP for both regimes is lower than the corrosion rate in the initial state, both for tests at room temperature and 37 $^{\circ}\text{C}$. Laws of weight loss rate change and evolving of hydrogen are similar and identical to the experimental errors (Table 3). Increasing of the test temperature to 37 $^{\circ}\text{C}$ does not significantly affect the corrosion rate, but increases within the experimental error. Only samples processed by ECAP for regime 2, which demonstrate significant growth both the rate of degradation and the rate of evolution of hydrogen, and samples in the initial state, whose hydrogen evolution rate also increases, are the exception. Probably, the higher corrosion rate after the second regime of ECAP compared with the first regime ECAP is caused by the existence of deformation twins in the structure, which can have a negative effect on the corrosion resistance of the alloy.

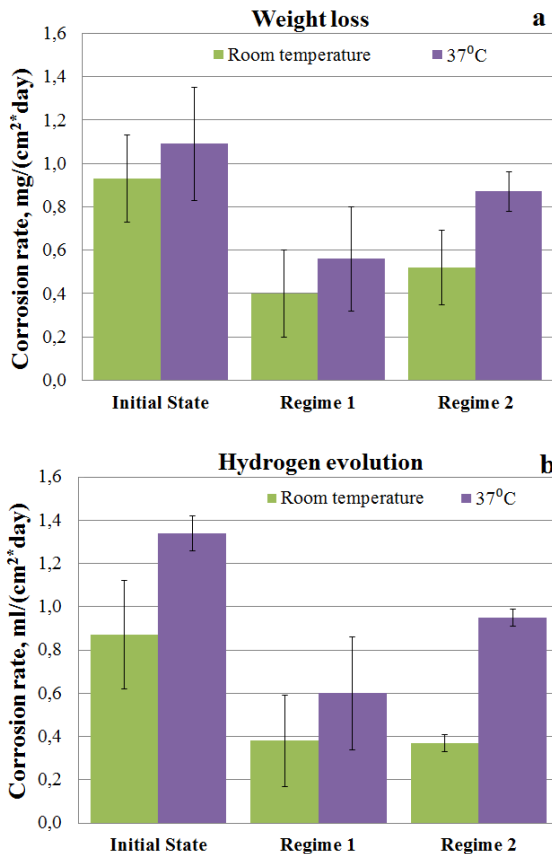


Fig. 4. Results of weight loss (a) and hydrogen evolution (b) tests at room temperature and 37 °C.

Table 3. Results of weight loss and hydrogen evolution tests of the WE43 alloy in the initial state and after ECAP treatment

Treatment	25 °C		37 °C	
	WL, mg/cm ² *day	HE, ml/cm ² *day	WL, mg/cm ² *day	HE, ml/cm ² *day
Initial state	0.93±0.20	0.87±0.21	1.09±0.24	1.34±0.26
ECAP Regime 1	0.40±0.17	0.38±0.04	0.56±0.09	0.60±0.04
ECAP Regime 2	0.52±0.09	0.37±0.16	0.87±0.08	0.95±0.07

The increase in corrosion resistance after deformation is apparently associated with a decrease in grain size caused by ECAP. The grain refinement affects the surface roughness parameters, which, in turn, affect the rate of degradation of the alloy.

4. Conclusions

1. ECAP leads to a significant refinement of the structure of the magnesium WE43 alloy. During the deformation process an UFG structure is formed with an average grain size of 0.69 - 1 μm, as well as Mg₁₂Nd phase particles with an average size of 0.41 - 0.45 μm.
2. The grain refinement during ECAP results in increasing of the ultimate tensile strength of WE43 alloy up to 300 MPa while the ductility increases up to 13.2%.
3. ECAP does not impair the resistance to electrochemical corrosion.
4. The corrosion rate, measured by the weight loss and hydrogen evolution methods, is reduced for both deformation regimes for tests both at room temperature and at 37 °C.

Acknowledgments

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MECHANICAL PROPERTIES OF STEELS WITH DIFFUSIONAL ZINC COATING OBTAINED BY NANOGALVANIZING PROCESS

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Abstract: Investigations of wear resistance and tensile strength of steel products with diffusional zinc coating obtained in zinc powders with a nanocrystallized surface of powder particles were carried out. The effect of the structural state of the coating on the wear resistance and adhesive grasping with a steel counterbody was established. The prospects of the nanogalvanizing process to improve the strength of steel products are shown.

The development of technologies in modern machine building aims at improving the mechanical and technological properties of the materials. The present study presents an improvement in the mechanical properties of low carbon steels by thermofusion coatings with nanofibers obtained under different heat treatment regimes. Depending on the type of heat treatment and the size of the zinc particles, different gradient layers can be obtained in depth. This of course reflects positively on the chemical resistance of the material. In addition, it positively affects the mechanical properties of the material by increasing mechanical strength and technological properties by improving the resistance to plastic deformation. With these first studies, there is an impetus for another look to improve the properties of low-carbon steels that are widely applicable in the field of machine building.

KEY WORDS: THERMODIFFUSION COITING, MECHANICAL TEST, VICKERS HARDNESS, MICROSTRUCTURE, TRIBOLOGY, SCRATCH TEST, WEAR RESISTANCE

1. Introduction

Wide application in mechanical and precision engineering is found in low-carbon steels. In spite of many research and knowledge, solutions are sought to improve their technological and mechanical properties [1, 2, 3]. Technologies have been developing at an intensive tempus in recent years, enabling materials to be improved and chemical properties guaranteed. This reflects on the price of the product, and different quality grades are sold on the market. Nonetheless, non-standard solutions are sought for the improvement of some technological parameters through additional technological processes - thermal treatment, plastic processing, coating or their combination. The present study aims to improve the mechanical properties of low-carbon steels by thermofusion coatings with nanoparticles obtained under certain heat treatment regimes. This treatment will improve the chemical resistance of the material and its technological workability in the deformation process with reduced frictional forces.

2. Experimental procedure

For the purpose of the study, three modes of thermofusion galvanizing on low-carbon steel were performed (Table 1). The first mode is heated to a temperature of 430 °C and a retention time of 15 minutes (Figure 1). At the same time, it is covered with a surface of zinc dust. In the process, the samples are cooled by sneaking to 150 °C and then to air. In the second mode, the heating temperature is lower and does not exceed 340 °C and retention for 15 minutes. Then the temperature rises to 370 °C over a retention time of 15 minutes, at the end of the mode, the samples are cooled down to 150 °C and then to air.

Table 1. Chemical composition of carbon steel of ordinary quality

Steel brand	Content of the elements %							
	C	Mn	Si	F	S	Cr	Ni	Cu
Steel 1	0.08	0.35	0.031	0.035	0.012	0.17	0.21	0.26

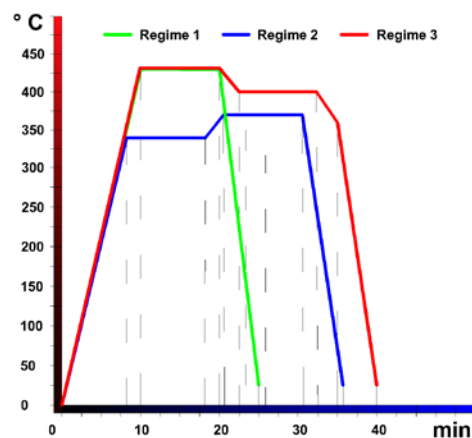


Fig.1. Temperature regimes of processing

The third processing mode in the initial stage coincides with mode 1 i.e. heating to 430 °C and holding for 15 minutes, after which the relaxation mode was realized at 400 °C for 15 minutes. At the end of the mode, the samples are kept in the heat chamber to a temperature of 150 °C, and then cooled to a sigh.

For the determination of the mechanical properties of one-dimensional uniform tension before and after thermofusion galvanizing of the steel, three test pieces of each mode according to the standard BDS EN 10002-1 (fig.1) are made. The initial working sizes of the samples are assumed to have a width $b_0 = 20$ mm, an initial computational base length $L_0 = 100$ mm with a material thickness $t_0 = 1.5$ mm and a total length $L_c = 200$ mm. The test was carried out on a universal test machine "Instron 3384" at a constant load speed of 5 mm / min (Fig.2.c).

For each test sample, an initial width of b_0 and a thickness t_0 with a micrometer with an accuracy of 0.01 mm shall be measured. Measured values are entered in the developed method as a correction for correct recalculation. It is also envisaged to introduce the change of b_0 and L_0 after the test b_k and L_k in the developed method for correct calculation of the mechanical characteristics.

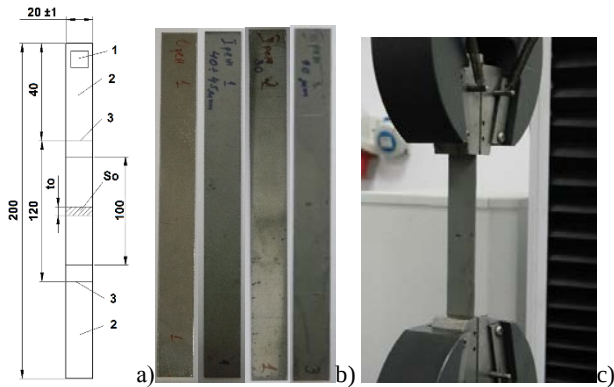


Fig.2. Mechanical tests for one-dimensional stretchin (a) test pieces made to the standard; (b) fabricated test pieces and after thermodiffusion galvanizing and (c) testing of test bodies

Hardness measurement was performed using the Vickers micrograph method with a load of 50 g according to ISO 6507-1 on the sample width in a condition of delivery and after thermodiffusion galvanization. The hardness was also measured in cross-section in the surface zinc layer area and in the diffusion zone.

A metallographic analysis was carried out by means of a NEOPHOT 21 microscope with a microstore attachment to a metallographic microscope.

3. Experiment results and discussion

The tested one-dimensional uniform tension test bodies in a delivery condition were processed and analyzed. They are also processed for each thermodiffusion galvanized mode. From the analysis it was found that the material in the delivery condition was heat treated (a strong pronounced yielding site) to remove the residual plastic deformation (Fig.3a Substrate). The mechanical strength deviation for the three test bodies is within a narrow range of 335.33 to 338.12 MPa, and the true strength is 561 MPa (Fig. 3b Substrate) and the true elongation does not exceed 31%. This result shows that the material is homogeneous and can be used for this study. After thermodiffusion galvanization the upper yield strength is shifted to higher values (Fig. 3a Regime 1, 2 and 3). This effect is atypical in thermal treatment. This phenomenon may be due to a surface zinc layer obtained and a low carbon steel depth diffusion zone formed of zinc-based intermetallic compounds. Samples treated by thermo-diffusion galvanization in Mode 2 show the highest yield limit of 347.67 MPa (Fig. 3a Regime 2) reaching the maximum material strength in its plated area of 353.33 MPa. Mechanical strength is highest at Mode 3 and reaches 355.67 MPa despite the lower yield strength. This is due to the thermo-diffusion galvanization mode, resulting in structural changes in the surface and depth in the base material.

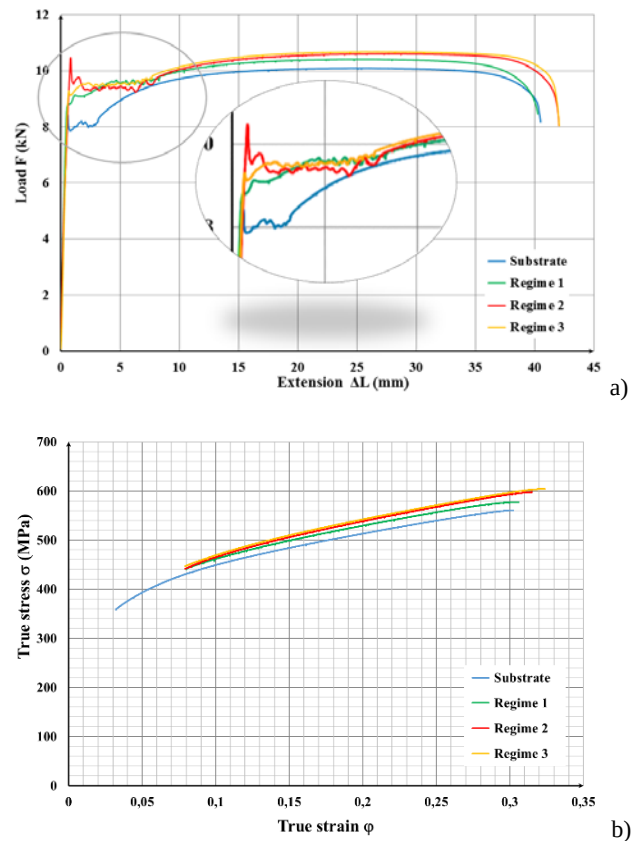


Fig.3. Mechanical characteristics (a) primary indicator diagrams; (b) a diagram of true strains and true deformations

The true strength of the true deformation after thermodiffusion galvanization is increased (Fig. 3b). The biggest change was found in mode 3 with 7.69% where the true strength reaches 604.11 MP relative to the blank. For the other two modes, the change is less, and for real mode 2, the true strength has increased by 7.44%, ie. 602.69 MPa, and for mode 2 the change is the smallest - the true strength has increased by 2.92%, i.e. 577.32 MPa compared to the delivery material. In this mode of thermodiffusion galvanizing, another positive effect associated with the preservation of the plasticity and the slight increase of the real plasticity in Mode 2 mode 3 was established, despite the effect of stiffening. The change in plasticity is up to 2.3%, ie. The true plasticity does not exceed 32.4% for the selected thermodiffusion galvanizing option.

In order to confirm the results obtained and to clarify the reasons for increasing the mechanical strength after thermodiffusion galvanization, a microstructural analysis of the steel surface was carried out under the condition of delivery and in Mode 3.

The metallographic images (Fig. 4a) show the presence of ferrite and cementite in the base material, the structure being well homogenized [4]. The material was heat treated at delivery as found by the one-dimensional uniform tension. The measured hardness of the material upon delivery on the surface is in the range of 132-144 HV0.05 (Fig.4.b), and after thermodiffusion galvanization the measured zinc surface hardness of the surface reaches 180-182 HV0.05, Surface hardness increased by 31.16%.

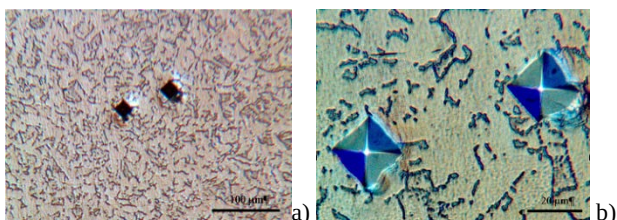


Fig.4. Microstructure of steel (a) on the surface at an increase of 125 $\times$; (b) Measured Vickers load on the surface at delivery rate 500 $\times$

The increased mechanical strength after thermodiffusion galvanization is also due to the formed diffusion layer, which consists of zinc-based intermetallic compounds. Figure 5 shows a microstructural cross-section of the zinc coating and a diffusion layer formed on the base material of the substrate. The average thickness of the zinc coating at mode 3 is in the range of 80-90 μm and the depth of the diffusion layer is within the range of 90-105 μm .

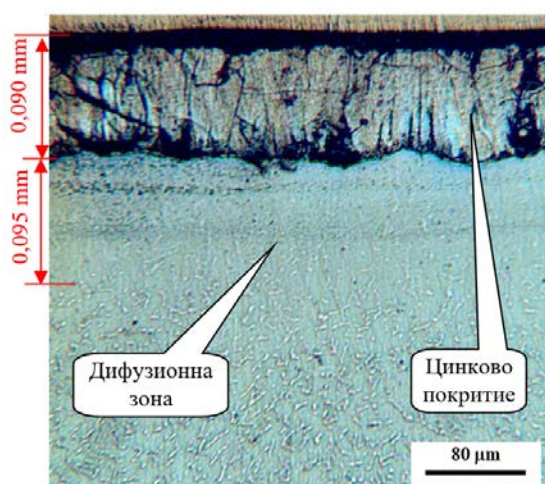


Fig.5. Thickness of the zinc coating at 125 $\times$ magnification

For the variation of the hardness from the surface to the parent metal, a series of measurements are shown in Figure 6 with a magnification of 125 $\times$. An increased hardness in the zinc layer has been found which varies widely from 333 to 396 HV0.05 (Fig.6-500 $\times$ magnification). These differences in this layer are due to the different phases created in the stair-building process.

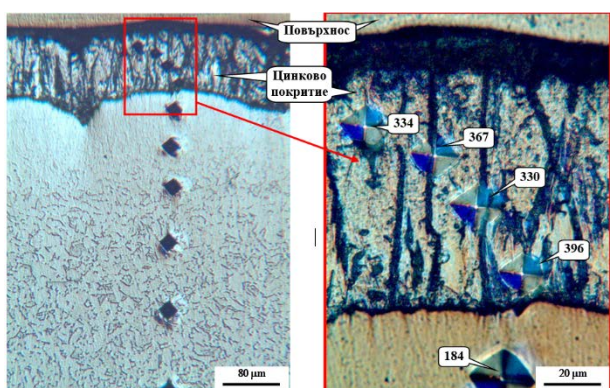


Fig.6. Microhardness of the zinc coating

The measured hardness at the top of the diffusion zone (Fig. 6) is 184 HV0.05 and is higher than the surface oxide layer (Fig.4.b), as with the increase of the depth the hardness decreases and reaches values 135-140 HV0.05. This diffusion zone contributes to

improving the mechanical strength of the surface as well as the better bond between zinc-coated metal. This will also improve corrosion resistance during the operation.

Wear behavior of diffusional coatings were studied as well. Steel samples with coatings of various thicknesses in the 30-90 μm range were tested according to ASTM G 65-94. Only δ -phase FeZn₇₋₁₀ was detected on the surface of al samples. The results show that the wear of the coatings is irregular (Fig. 7). The highest wear rates are observed for coatings with large thickness at the beginning of the test. Also, a sharp increase in the wear rate is observed at the moment of crossing the phase boundary $\delta / \delta + \Gamma$ in the coating. The lowest wear rates are obtained for coatings up to 30 μm thick characterized by smooth profiles of the chemical and phase composition.

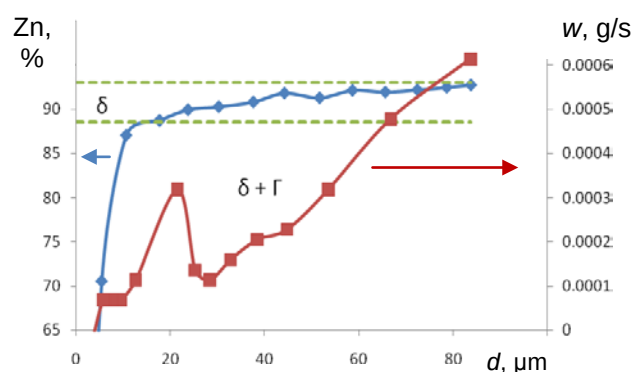


Fig.7. Zinc content (weight %) and wear rate as functions of coating's thickness

Microscopic inspection of the steel counterbody after test show that the transfer of the iron-zinc phases from the thick ($d > 30 \mu\text{m}$) coatings on the surface of the counterbody occurs (Fig. 8). Together with high wear rates for such coatings it suggests that at first stage the wear is adhesive. After this transfer the friction pair coating-steel becomes symmetric, so these coatings may act as solid lubricants, e.g., in threaded joints. Recent industrial tests [5] showed the feasibility of this approach.

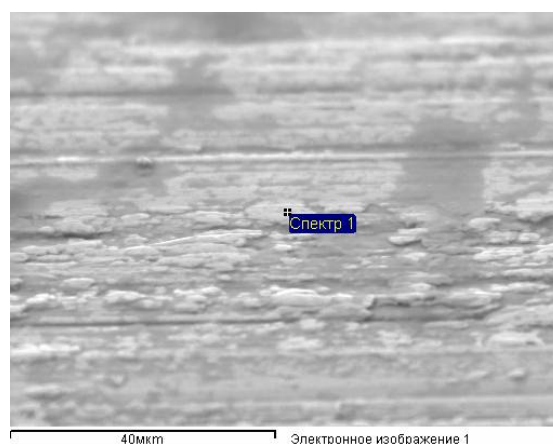


Fig.8. SEM image of the steel counterbody after wear test. Chemical composition at the marked point: Fe 25.2 %, Zn 74,8 %

According to our previous studies of the structural state of diffusional zinc coatings [6] the surface layers of δ -phase in a relatively thick diffusional coatings (more than 30 μm) are characterized by the absence of the texture, whereas the inner layer ($< 30 \mu\text{m}$) of the coating has texture, characterized by the

hexagonal axis of δ -phase directed parallel to the plane of the coating as in usual hot-dip coatings. Thus, both observed effects are closely related to the structure of δ -phase layer.

4. Conclusions

From the initial tests of the mechanical properties of steels galvanized by thermo-diffusion galvanization, we established:

- The true mechanical strength is increased to 7.69 % in the thermodiffusion galvanization mode;
- The improved upper yield strength after thermodiffusion galvanizing increases from 8.87 % to 25.06 %;
- The formed zinc diffusion layer is in the range of 80 to 105 μm and the hardness in the layer increases to 31 %;
- At the initial stage of wear of zinc coatings with a thickness of more than 30 μm , the coating is transferred to a steel counter surface

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INVESTIGATION OF HEAT RESISTANCE AND STRUCTURE OF LAYERED REFRACTORY COMPOSITES REINFORCED BY CHEMICAL COMPOUNDS WITH SILICON, CARBON, AND BORON

ИССЛЕДОВАНИЕ ЖАРОПРОЧНОСТИ И СТРУКТУРЫ СЛОИСТЫХ ТУГОПЛАВКИХ КОМПОЗИТОВ, УПРОЧНЕННЫХ ХИМИЧЕСКИМИ СОЕДИНЕНИЯМИ С КРЕМНИЕМ, УГЛЕРОДОМ И БОРОМ

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Abstract: In contrast to the melting technologies for the production of high-temperature alloys in the solid-phase technology developed by us, a multi-layer structure of the future composite material is already set at the initial stage of the billet formation. In the work presented, the billets were assembled from Nb- and Mo-foils with one or two-sided coatings of carbon or Si-B. Layered structures of composites were formed during the diffusion welding of packets at 1500°C and a pressure of ~14 MPa. In the place of the coatings, layers of high-temperature carbides or intermetallic Si and B compounds with Nb and Mo formed, which occupied up to ~40% of the cross-sectional area of the composites. The strength and crack resistance at room temperature, strength at a temperature of up to 1500 °C, as well as the modulus of elasticity and density were measured. The presence of intermetallides in the structure of composites leads to a decrease in their density and an increase in the modulus of elasticity.

KEYWORDS: HEAT RESISTANCE, CRACK RESISTANCE, LAYERED COMPOSITE, LAYERED STRUCTURE, METAL MATRIX, SOLID-PHASE TECHNOLOGY, DIFFUSION WELDING, BENDING TESTS, INTERMETALLIC COMPOUND, MODULUS OF ELASTICITY.

1. Introduction

The result of many years of research on the heat resistance of alloys for the aviation industry, which began in the early 1970s, were alloys of the Ni-Al system. An important characteristic of a heat-resistant material is its operating temperature. The use of structural elements intended to work at elevated temperatures is always limited by the specific strength of the alloy from which they are made. This circumstance is due to the fact that an increase in the operating temperature with simultaneous increase in the mechanical characteristics of the alloy leads to a rapid expenditure of its strength capabilities.

Due to this, at present, heat-resistant (Ni-Al)-alloys, whose maximum melting point is slightly over 1600°C, began to fail to meet the ever-increasing demands of the industry. To date, they have reached their ceiling of operating temperatures equal to of ~1150°C, and they need an effective replacement.

Arising from this flow of information on heat-resistant materials instead of Ni-Al system produced, mainly smelting technology continues unabated. Most of the research fall on niobium and molybdenum alloys with silicon and, to a lesser extent, on Nb-Al alloys with intermetallic hardening. But the melting method for the manufacture of products from heat-resistant alloys, in particular gas turbine engine blades, is precision investment casting, which was developed for the Ni-Al system. For high-temperature alloys Nb-Si and Mo-Si practical realization of such a casting is associated with the need to develop new refractory and inert with respect to melt the ceramic materials for the crucibles.

We have proposed and for almost a decade has been developing a solid-phase technology for obtaining composite heat-resistant materials of a layered type. It differs from traditional methods of melting, for example, the method of directional crystallization, in that the formation of the desired structure occurs at the solid-phase interaction of layers, and the multilayeredness and orientation of the structure is created at the initial stage of the assembly of the packet. Heat resistance is provided by the creation of 2-dimensional planar layered structures of intermetallic compounds or carbides, and high crack resistance by a metal matrix, which often has its own layered structure. We call it a second-order structure. Solid-phase methods of obtaining heat-resistant composite materials have recently shown increasing interest.

The essence of solid-state technology can be understood from the following description. Layered composites consisting of

alternating layers of intermetallic compounds and layers of Al solid solution in niobium Nb(Al) were obtained as a result of diffusion interaction between Nb- and Al-foils during the diffusion welding of Nb/Al packets using pressure [1, 3]. As in our studies [3-5], the phase composition of the interaction zone between niobium and aluminum depended on the ratio t_{Nb}/t_{Al} , where t_{Nb} and t_{Al} are the foil thicknesses of niobium and aluminum, respectively, and the final welding temperature. After 1500°C in a composite with $t_{Nb}/t_{Al} = 1.4$, a structure was formed from Nb(Al), Nb₂Al, and Nb₃Al.

The Nb-Al system is most simple for the use of solid-state technology in that aluminum is a deformable metal. This makes it easy to form the original multilayered packets from Nb- and Al-foils. To study the heat resistant layered composites with silicides, carbides and borides during assembly of source packets used metallic ribbons, respectively with coatings of silicon, carbon and boron or mixtures thereof, applied by various methods.

The relevance of this work is to obtain and investigate the heat-resistant material, which we believe can operate at higher temperatures than not only the currently widely used (Ni-Al)-alloys, but also alloys based on the Nb-Al and Nb-Si systems with intermetallic hardening. As follows from our studies [6-8], alloys of niobium with a directed eutectic (Nb)-Nb₅Si₃ at temperatures above 1300°C begin to degrade.

To achieve a higher temperature level of heat resistance than that of the Nb-Si alloy, it is proposed to start by alloying its silicide's with carbon and boron. For example, the NbB₂ boride melts only at ~3000°C. This is almost 500°C higher than the melting point of the silicide Nb₅Si₃ and exceeds the melting point of Nb₃Al by more than 900°C. Similar studies have been started with the Mo-Si system. It was shown in [9] that the Mo-Si-B ternary alloys possessed good heat-resistant properties at high temperatures.

The interaction of the components and the formation of the orientation of the structure occurred in multilayered packets composed of Nb and Mo foils with (Si-B) or (Si-C) coatings, during their diffusion pressure welding. Multilayered composites of niobium with carbide hardening were also studied. In this case, multilayer packets of Nb-foils with a pyrolytic coating were welded.

2. Composites Nb-Si-B u-Mo-Si-B

Packets assembly. The Nb/(Si-B)- and Mo/(Si-B)-packets were assembled from Nb- and Mo-foils with an (Si-B) coating (Table 1). Suspensions from a mixture of Si- and B-powders with a Si/B ratio of 3 in polyethylene glycol were applied to the foils by the

"staining" method. The width and length of the packets are 35 and 40 mm, respectively. The direction of the rolling foils – along the length of the package.

Diffusion welding (DW). Welding of packets was carried out in a vacuum (not lower than 10^{-4} mm Hg) installation with a graphite heater designed for a maximum temperature of 1700°C and a maximum load of 10 T. Polyethylene glycol was evaporated, starting from ~ 200°C, as the packet was heated.

Table 1. Description of packets and modes of diffusion welding

Package escription and DW modes	Quantity, pcs.
Mo/(Si-B)-1 packet	
Mo-foil 50 μ m thick with 2-sided (Si-B) coating	15
Mo-foil 50 μ m thick with 1-sided (Si-B) coating	2
Total number of Mo-foils	17
The total number of double (Si-B)-coverings	16
Weight of all Mo-foils without coating – 10.370 g	
The weight of the packet after DW is 10.880 g	
The weight of all (Si-B) coatings is 0.510 g or 4.7% by weight	
The thickness of the packet after DW is 1.10 mm	
DW: 1500°C, 30 min at 10.5 MPa (1.5 T) + 30 min at 14.0 MPa (2 T)	
Nb/(Si-B) packet	
Nb-foil 60 μ m thick with 1-sided (Si-B) coating	21
Nb-foil 60 μ m thick without (Si-B) coating	1
The total number of Nb-foils	22
The total number of (Si-B)-coverings	21
The weight of the packet after DW is 17.315 g	
The thickness of the packet after DS is 1.7 mm	
DC: 1500°C, 1 ч при 14.0 MPa (2 T)	

Layered structure studies

Composites of Mo/(Si-B). The macrostructure of the cross-section of the Mo/(Si-B)-1 composite (Figure 1) after diffusion welding consisted of alternating layers of a light background and an interaction zone (IZ) between molybdenum and an (Si-B) coating. IZ were uneven in thickness – from their total absence to ~ 70 μ m. At a thickness of 40-70 μ m (Fig. 2a), it has a large number of Kirkendal pores inside. In pores of 20-30 μ m thick, the pores were kept in an insignificant amount (Fig. 2b). It would seem that with an even smaller thickness, the number of pores would have to decrease and result in their total absence. But, starting from a thickness of ~ 20 μ m, both the absence of pores and the existence of voids with a length of up to several hundred microns were observed. And so down to the complete absence of the diffusion layer. Such an ambiguity in the change in the structure of IZ at their small thicknesses can be explained by the fact that such voids can form in the place of a fragile and not strong intermediate phase and, therefore, tend to locally crumble at the preparation of a metallographic section for microscopy.

In the Mo-layers near and at a certain distance from the IZ, the boron content varied within the limits of 17-28 at.% and almost no silicon. However, according to their state diagrams with molybdenum, at 1500°C the solubility of boron in Mo is very small, and silicon can be dissolved up to ~ 2 at.%. The compositions obtained correspond to the eutectic region Mo(B) + Mo₂B of the Mo-B diagram, where Mo(B) is a solid solution of boron in Mo.

Phase structure of interaction zones. Their extreme layers of thickness ~ 10 μ m bordering the Mo(B) + Mo₂B layers consisted of molybdenum boride Mo₂(B,Si) with silicon dissolved in it. The averaged Mo, B, and Si contents in them are Mo_{1.87}(B_{0.99}Si_{0.14})_{1.13} and Mo_{1.74}(B_{1.22}Si_{0.04})_{1.26} for the IZ in Fig. 2a and b, respectively. That is, in the boride Mo₂B, which is located in the IZ with a small amount of pores, Si is much less dissolved.

In the IZ with a porous middle between it and Mo₂(B,Si), there were 2-phase regions 20-25 μ m thick (see Fig. 2a) consisting of intermetallic compounds Mo(B,Si) $\equiv$ Mo_{1.06}(B_{0.63}Si_{0.31})_{0.94} and Mo₅(Si,B)₃ $\equiv$ Mo_{4.29}(Si_{2.42}B_{1.29})_{3.71} or solid solutions of Si in α MoB

and boron in the silicide Mo₅Si₃, respectively. An analogous phase composition had the middle region of IZ in Fig. 2b.

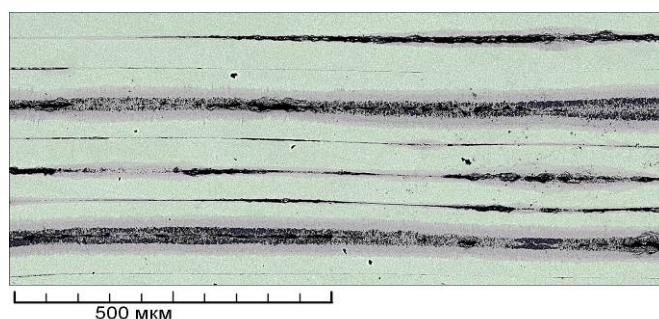


Fig. 1. The macrostructure of the cross-section of the Mo/(Si-B)-1 composite, which coincides with the Mo-foils rolling plane

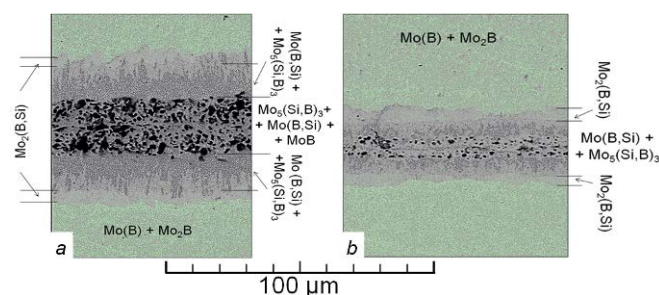


Fig. 2. Composite Mo/(Si-B)-1. The microstructure of the interaction zones between Mo and the coating with porous middle (a) and with a small number of pores (b)

The middle of pollutants with a large number of pores (see Fig. 2a) consisted of two phases: Mo₅(Si,B)₃ and Mo(B,Si). The Si and B concentrations in the Mo₅(Si,B)₃ compound varied in favor of boron from 35.0 Si and 3.4 at.%B to 23.1 Si and 14.4 at.% B or from Mo_{4.93}(Si_{2.80}B_{0.27})_{3.07} to Mo_{5.00}(Si_{1.85}B_{1.15})_{3.00}. A similar composition change was observed in the Mo(B,Si) boride: from 37.9 B and 19.2 at.%Si to 42.0 Mo + 57.8 at.%B or from Mo_{0.86}(B_{0.76}Si_{0.38})_{1.14} to Mo_{0.84}B_{1.16} (+ 0.13 at.%Si).

Composite Nb/(Si-B). Unlike Mo/(Si-B), the cross-sectional structure of a composite with Nb was regular (Fig. 3a). Zones of interaction (IZ) formed in situ (Si-B)-coatings occupying ~ 40% of the cross-sectional area were alternated with bright layers of boron solid solution in niobium Nb(B): from ~ 0 to 3.85 at.%B.

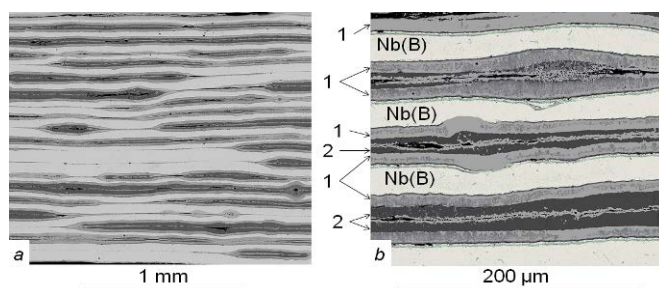


Fig. 3. Macro- (a) and microstructure (b) of the cross-section of the Nb/(Si-B) composite after DW in a plane parallel to the rolling direction of Nb-foils

We will trace the phase composition of the IZ with the help of Fig. 3b. Two of its outer layers of gray (1) bordering with Nb(B) consisted of the intermetallic compound Nb₅(Si,B)₃, as the main (matrix) phase and inclusions of Nb(B,Si). The composition of Nb₅(Si,B)₃ varied from the silicide Nb₅Si₃ (boron-free) to Nb_{5.24}(Si_{1.76}B_{1.00})_{2.76} with 12.5 at.% boron. The composition of the inclusions corresponded to the formula Nb_{1.03}(B_{0.74}Si_{0.23})_{0.97}.

The thin inner layer and the intermediate layers of dark color (2) were single-phase and consisted of ternary intermetallic compounds Nb(Si,B) $\equiv$ Nb_{1.01}(Si_{0.59}B_{0.40})_{0.99} and Nb(Si,B)₂ $\equiv$ Nb_{0.92}(Si_{1.59}B_{0.49})_{2.08}, respectively.

Characteristics of high-temperature strength of composites.

The fracture toughness evaluation was carried out on samples with a lateral notch, and to calculate the critical factor of stress intensity K^* under the conditions of plane deformation, the formula [10] was used: $K^* = (PS/BW^{3/2}) \cdot f(a/W)$, where P is the maximum load, S is the distance between the supports, B and W are the thickness and height of the sample, and a is the value of the lateral incision along the vertical. Tests of Nb/(Si-B) composites on crack resistance and strength at room temperature were carried out at a perpendicular ($\perp$) and parallel ($\parallel$) application of the load with respect to the surface of the layers.

Anisotropy of the structure of the material, led to a difference in the values of K^* , as well as the variance of their values. The following fracture toughness values were obtained: $K^*_{\perp} = (13,0 \pm 1,3)$ and $K^*_{\parallel} = (12,0 \pm 0,5) \text{ MPa} \cdot \text{m}^{1/2}$. The values of K^* show that the material occupies an intermediate position between traditional ceramics and high-strength metal alloys.

The strengths σ_B when the load is applied in directions perpendicular and parallel to the plane of the layers are $\sigma_{B\perp} = (600 \pm 180) \text{ MPa}$ and $\sigma_{B\parallel} = (790 \pm 48) \text{ MPa}$, respectively. The higher strength with parallel layer load can be explained by the higher moment of resistance at bending of high modulus and high strength "boridosilicidal" layers than with the load perpendicular to the layers.

In Fig. 4 the results of testing for the composites Nb/(Si-B) and Mo/(Si-B) at high temperatures in the range 1100–1500°C are shown. The dependence $\sigma_B(T)$ draws attention to the fact that the values of the strength of about 250 MPa, which are satisfactory for such temperatures, remain in the entire high-temperature interval.

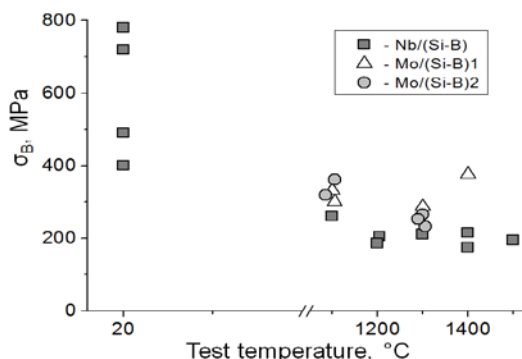


Fig. 4. Dependence of the strength σ_B of the composite samples Nb/(Si-B) and Mo/(Si-B) on the test temperature at a perpendicular load application with respect to the surface of the layers

3. Composites with carbide-silicide hardening

1. A composite obtained from a packet with 30 Nb-foils having a one-sided suspension coating from a mixture of Nb-Ti-Cr-Mo-Si-Al-ZrH₂ powders was studied. Welding of the packet and solid phase formation of the layered structure occurred at 1500°C under a pressure of 8.4 MPa for 5 hours in a CO atmosphere. The macro- and microstructure of the cross section of the packet is shown in Fig. 5.

Three strengthening phases are distinguished, different in composition and color contrast: 1) TiC carbide with 47.3 ± 0.8 Ti and 51.2 ± 1.1 at.% C, in which are dissolved from 0.4 to 1.1 Nb and from 0.4 to 0.7 at.% Zr; (2) carbidosilicide $\text{Me}_{0.975}(\text{C}_{0.51}\text{Si}_{0.49})_{1.025}$ containing 29.5 ± 5.4 Ti, 11.7 ± 4.6 Nb, 5.4 ± 0.6 Zr, 1.3 ± 0.1 Al, 0.7 ± 0.5 Mo and ~ 0.2 at.% Cr; (3) Nb₅Si₃ intermetallide containing 53.7 Nb, 30.6 at.% Si, and 15.0 at.% C, the balance being 0.45% Ti and 0.2 at.% Cr; (4) pores formed during the grinding of the sample, in places where the brittle phase is deposited.

The remaining volume was a layered viscous-plastic matrix whose composition varied from Nb-solid solution with ~ 99.5 wt.%Nb to (Nb-Ti)-alloy with 67–76% Nb and 20–15 wt.%Ti. Significant concentrations have: Mo – from 1.1 to 5.6%, Cr – from 1.7 to 2.0% and Al – from 0.8 to 1.1% by weight. In addition, the alloy contains silicon – from 0.3 to 0.4 wt.% and a sufficient

amount of carbon from 2.8 to 4.8 wt.% (15.3 – 24.4 at.%). And also in the matrix there are inclusions corresponding to carbide Me₂C, where Me = Nb (52.8%), Ti (8.85%), Cr (1.15%) and Mo (0.9 at.%). Carbon is contained in an amount of 34.9 at.%.

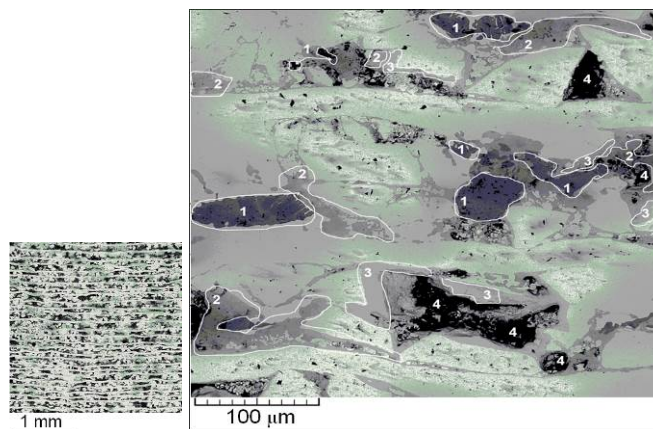


Fig. 5. Macro- (left) and microstructure of the composite (right): 1, 2 and 3 - strengthening phases; 4 - pores

Mechanical tests using the 3-point bending method at 1100–1300°C showed the following results: the stretch of proportionality $\sigma_{PR} = 200\text{--}370 \text{ MPa}$, $\sigma_B = 260\text{--}390 \text{ MPa}$. At room temperature, $\sigma_B = 320\text{--}540 \text{ MPa}$.

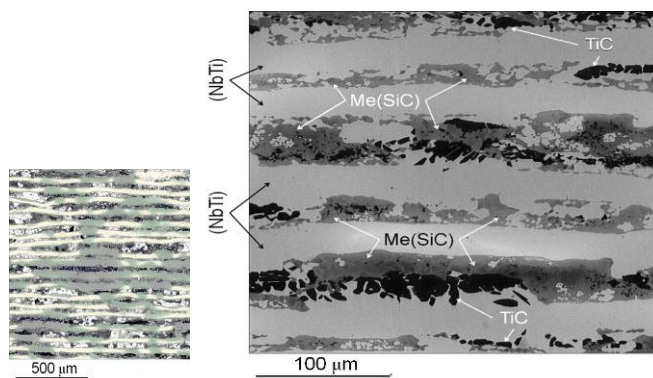


Fig. 6. Macro- and microstructures of the composite after welding at 1500°C and 14 MPa pressure for 3 hours in an atmosphere of CO

2. Composite samples 2–4 thick and $\sim 30\text{--}40 \times 60 \text{ mm}$ in size were prepared by welding of multilayered packets composed of 30 Nb-foils $30 \mu\text{m}$ thick with a coating similar to the previous one, but without Nb: 49.1Ti–19.8Mo–12.4Si–12.1ZrH₂–3.8Cr–2.8 wt.%Al.

The multilayer structure (Fig. 6) consisted of layers of a multicomponent alloy (Nb, Ti) of thickness $\sim 30 \mu\text{m}$ alternating with interlayers of approximately the same thickness from the strengthening phases. The following phases are identified.

1. TiC carbide with 50.4Ti and 47.7 at.%C, in which 1.0%Nb and 0.6 at.%Zr are dissolved.

2. Carbo-silicide $\text{Me}(\text{Si,C}) \equiv \text{Me}_{1.05}(\text{Si}_{0.51}\text{C}_{0.44})_{0.95}$ with content of the elements: 27.8Ti–14.5Nb–6.9Zr–2.5Al–0.6Mo–0.3 at.% Cr and 47.4 at.%(C + Si).

3. Viscous-plastic structural component (Nb,Ti), the composition of which (based on the Nb–C diagram) varied from the hypereutectic region $\beta\text{-Nb}_2\text{C} + (\text{Nb})$ with 33.4 Nb and 30.1 at% Ti to the Nb-solid solution with 91.6Nb and 5.6 at.%Ti. The content of C varied from 22.1 ± 2.7 to ~ 0.2 at.%.

4. Niobium composites with carbide hardening

Before the assembly of the Nb/CNbC/CNbC/... packets, CNbC foils were prepared. These are Nb-foils with a 2-sided pyrolytic coating deposited in one experiment on both surfaces of niobium at 1100°C by decomposition of methane CH₄. Two modes of DW packets were used: 1500°C for 30 min and 2 h at a pressure of 8.2 and 32.7 MPa, respectively.

The light layers (Nb) in both composites were an Nb-solid solution with a carbon content of 1.2 ± 0.6 and 0.5 ± 0.4 wt.% (Figures 7a and b, respectively). Solid gray layers in the composite 1CNbC/CNbC (a) - Nb₄C_{3-x} carbide with a concentration of 37.2 ± 1.6 at.%C. The same layers in the 2nd composite (b) contained 24.7 $\pm$ 1.1 at.%C and consisted of Nb₂C carbide.

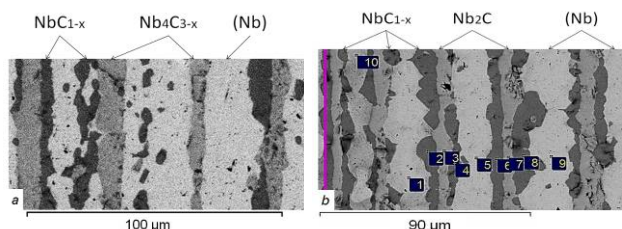


Fig. 7. Microstructure of the composites 1CNbC/CNbC and 2CNbC/CNbC after DW for 30 min under a pressure of ~8 MPa (a) and 2 h under a pressure of ~33 MPa (b), respectively

Discrete inclusions of dark color located along the boundaries of continuous carbide layers in 1CNbC/CNbC and 2CNbC/CNbC composites contained 61.5 ± 3.5 and 54.8 ± 1.5 at.% C, respectively, which is more than 50 at.%, and exceeds the boundaries of the NbC_{1-x} existence region. But there are no other niobium carbides other than NbC_{1-x} with a carbon content exceeding the C content in Nb₄C_{3-x}. Therefore, we believe that dark inclusions are nothing more than carbide NbC_{1-x}.

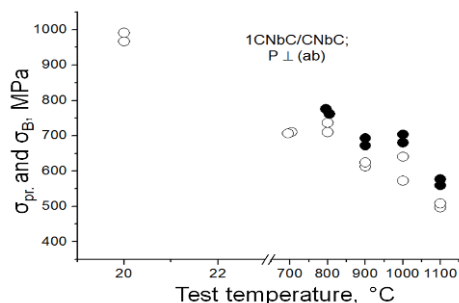


Fig. 8. Dependences of σ_{PR} (○) and σ_B (●) on the test temperature for the 1CNbC/CNbC composite at $P \perp (ab)$

The results of mechanical tests at temperatures up to 1100°C and a load P perpendicular to the layers were carried out for a composite with DW for 30 min. Voltage σ_B in the temperature range from 700 to 1100°C dropped ~750 to ~550 MPa.

5. Conclusion

1. By solid-state interaction in process of diffusion welding of multilayer packets composed of thin Mo- and Nb-foils with suspension (Si-B) coatings layered composites containing intermetallic of metals with B and Si as potential hardening phases were obtained. Room strength flexural tests for perpendicular ($\perp$) and parallel ($\parallel$) orientations of load application and rolling direction of Nb-foil showed $\sigma_{B\perp} = (600 \pm 180)$ and $\sigma_{B\parallel} = (790 \pm 48)$ MPa. A significant variance for $\sigma_{B\perp}$ leveled the expected difference in strength values $\sigma_{B\perp}$ and $\sigma_{B\parallel}$. High-temperature tests of Nb/(Si-B) and Mo/(Si-B) composites in the interval 1100-1500°C showed a satisfactory result for such temperatures – the strength of $\sigma_{B\perp}$ of the order of 250 MPa, which was preserved throughout the temperature range. The tests for crack resistance showed that the material occupies an intermediate position between ceramics and high-strength metal alloys. But composites have the potential to increase it by optimizing the microstructure of the interaction zones, varying the parameters of DW. The studies were of a "pilot" nature. Both composites have reserves for increasing fracture toughness. Studies on creep resistance at high temperatures and optimization of the initial composition and regimes of DW are also necessary. This determines the direction of further research.

2. With the example of composites prepared by welding of multilayer packets made up of Nb-foils with suspension

multicomponent coatings, it has been shown that by solid-state technology can produce layered composites with structures of a viscous-plastic matrix and high-temperature carbide and carbide-silicide phases. Carbon contained only in the atmosphere of the chamber in the form of CO at a residual pressure of $\sim 10^{-4}$ mm Hg. Due to its atomic mobility, it penetrated into the structural components of the composites. With the participation of carbon, strengthening phases in the form of (Ti-Nb)-carbide and layers of carbide-silicide compounds Me(C,Si) were formed.

3. A composite with a layered structure hardened by carbide layers was prepared by the DW under the pressure of multilayer packets of Nb-foils with a 2-sided pyro-carbon coating. Its structure was characterized by the alternation of the layers of the solid solution C in Nb and the layers consisting of NbC_{1-x} and Nb₂C or NbC_{1-x} and Nb₄C_{3-x} carbides. The stretch of proportionality of PC at room temperature of such composites was 935-980 MPa. For a multilayer Nb/Nb composite, the $\sigma_{PR} = 290-300$ MPa. At 1100°C, a layered composite containing 33.6% by volume of carbide layers had σ_{PR} of 495-510 MPa.

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THE INFLUENCE OF SULFONE-T FIBER CONTENT ON TECHNICAL CHARACTERISTICS OF ORGANOPLASTICS BASED ON AROMATIC POLYAMIDE

ВЛИЯНИЕ СОДЕРЖАНИЯ ВОЛОКНА СУЛЬФОН-Т НА ТЕХНИЧЕСКИЕ ХАРАКТЕРИСТИКИ ОРГАНОПЛАСТИКОВ НА ОСНОВЕ АРОМАТИЧЕСКОГО ПОЛИАМИДА

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Abstract: In this paper, the possibility of creating new structural organoplastics based on aromatic polyamide of phenylone, fiber-reinforced sulfone-T, is considered. Analysis of the results of physical and mechanical properties showed that, on the one hand, the introduction of an organic fiber into the polymer matrix leads to an increase in hardness, modulus of elasticity, and Poisson's ratio of 1.7; 1.9 and 1.3 times, respectively, on the other hand, there is an insignificant increase in the relative strain and yield stress at compression in the range of 10%, which is due to the presence of micropores formed at the polymer-fiber interface in the structure of organoplastics with the introduction of fiber filler over 15 wt.%. An increase in wear resistance of 1.6 times was observed, while a reduction in the coefficient of friction by 60%, compared with pure phenylone. Positive results of the research made it possible to switch to industrial ones - replacement of roller bearings of pins on sliding bearings made of polymeric composite material, which led to an increase of 3-4 times the working life as compared to serial ones.

KEYWORDS: AROMATIC POLYAMIDE, ORGANIC FIBERS, ORGANOPLASTICS, STRENGTH CHARACTERISTICS, TRIBOTECHNICAL CHARACTERISTICS

1. Introduction

Today, the world industry of plastics has moved far ahead. Polymer products are widely used in various industries. According to PlasticsEurope data for 2014, the world produced about 311 million tons of polymer products (including thermoplastics, polyurethanes, thermoreactive polymers, adhesives and sealants, as well as polymer coatings and seals). Europe accounted for about 59 million tons of this "pie" (19%). This result allows Europe to take the second place in terms of production of plastic products in the world. In Europe itself, leading manufacturers in the production of polymer products are industrial leaders: Germany, Italy, France, Great Britain and Spain. They account for about 75% of all the plastic produced in Europe [1].

It is doubtful that the automobile and engine manufacture could find the economic (and other) incentive necessary to develop alternatively fuelled products strictly on their own volition.

2. Preconditions and means for resolving the problem

Mechanical engineering today is experiencing an upsurge, and as a result, there is a growing need for new polymer products used both in the automotive industry and for domestic use. This direction takes 18% of the world consumption of polymers, yielding to building polymers by only 4% [2]. The increase in the service life of the structures largely depends on the reliability of the moving joints, which are subject to high loads, high speeds and temperatures. Therefore, there is a need to create new materials that could meet such requirements. Among the existing polymer composite materials (PCM), organoplastics, also called multifunctional materials, are of particular interest. They differ from the typical representatives of PCM by the polymeric nature of both components - matrices and fibers, characterized by high strength, low density and thermophysical characteristics [3]. They are widely used for the manufacture of products for various purposes: structural, electrical and radio engineering, heat insulation and others.

3. Solution of the examined problem

The purpose of this work was the development and investigation of the performance characteristics of new polymer composite materials based on aromatic polyamide phenylone, reinforced with organic fiber sulfone-T.

4. Methods and subjects of investigation

Phenylone aromatic polyamide C-1 (TS 6-05-221-101-71) was used as a binder; this represents finely divided pink powder with a bulk density of 0.2 - 0.3 g / cm³ and a specific viscosity of 0.5 % in dimethylformamide solution with 5 % of lithium chloride not less than 0.75, characterized by the following properties: density of 1.35 g / cm³, toughness of 20 kJ / m², hardness of 18 HRB, the tensile breaking stress of 100 MPa. Phenylone is reinforced by thermostable organic fibers sulfone-T with the following characteristics: the length of a no. 8-9 fiber is 3 mm, the strength is 240- 270 mN/tex, elongation at breakage is 17-21%, and the twist is 120-140 tpm.

Press-composition of the compound: phenylone +5-20 mass % of organic fibers was prepared by mixing the components in a rotating electromagnetic field in the presence of ferromagnetic particles. The tablets were charged in a mold preheated to 523 K, heated to 593-598 K and maintained at this temperature for 10 min, 10 min without pressure and under pressure of 30 MPa. To fix the shape of a product, the goods were cooled under pressure to a temperature of 523 K and pushed out of the mold later.

Brinell hardness was measured by indentation under a given load on the hardness tester BTSHPSP GOST 46-70-77 and specific toughness, which is a dynamic test of polymers, a single blow bending according to GOST 4647-69. Compressive yield point was determined on a test machine with the mechanical loading of the sample and mechanical force measure, Universal servo test machine UIT STM (GOST 4651-2014). The investigation of tribological properties in the frictionless mode was carried out at room temperature on a friction disk machine. The wear of the sample was evaluated according to the disk scheme (steel 45, HRC 50, Ra 0.08) - a composite finger (Ø 10, 10 mm high) at a specific load of 0.4-1.0 MPa, sliding speed of 1 m / sec, friction paths of 1000 m. The wear of the samples was determined on analytical scales VLR-200 with an accuracy of 0.0002 g. The microstructure of the samples after the tests was examined with an optical microscope Biolam-M at an increase of 200 times.

5. The results and their discussion

The most complete use of the strength of reinforcing fibers in organoplastics is achieved when, along with high adhesion and wetting power, the binder possesses a set of properties that allows for joint work of the fibers during deformation and the greatest monolithic nature of the system [4], i.e. uniform distribution of organic fiber within the binder. Investigation of the microstructure

of the obtained samples showed that the chosen method of mixing and pressing the compositions with a content of 5-20 wt. % of sulfone-T fiber in the polymer matrix of phenylene provides an ideal distribution of reinforcing fibers (Figure 1). Analysis of the results of physical and mechanical properties showed that, on the one hand, the introduction of an organic fiber into the polymer matrix leads to an increase in hardness, modulus of

elasticity, and Poisson's ratio of 1.7; 1.9 and 1.3 times, respectively; on the other hand, there is an insignificant increase in the relative strain and yield stress at compression around 10%, which is due to the presence of micropores formed at the polymer-fiber interface in the structure of organoplastics and the lack of the uniformity of the filler distribution at the introduction of organic fiber more than 15 wt. % (Figure 2).

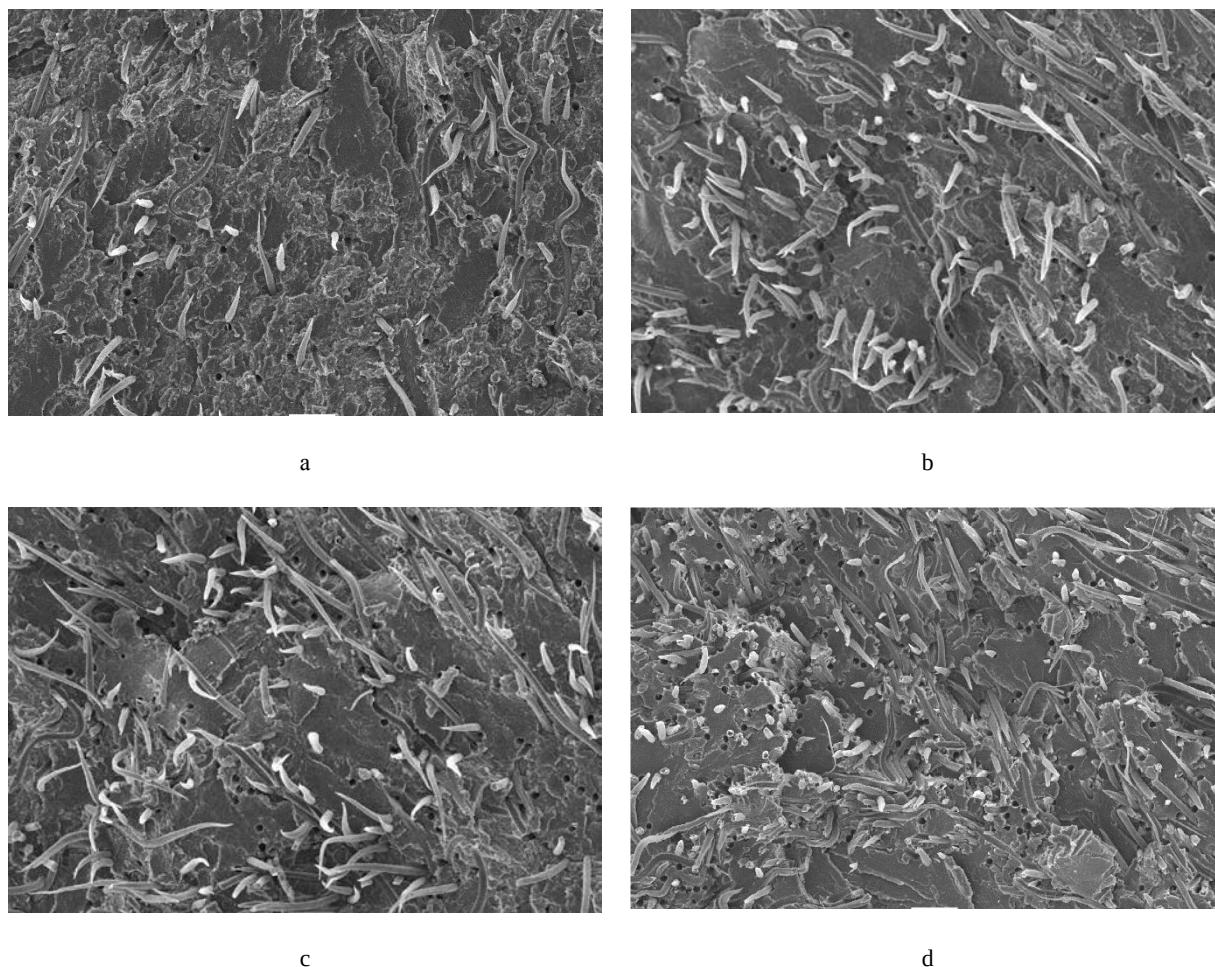


Fig.1. Electronic microphotographs of the starting polymer (a) and organoplastics based on it, containing 5 (a); 10 (b); 15 (c) 20 (d) wt% of the fiber

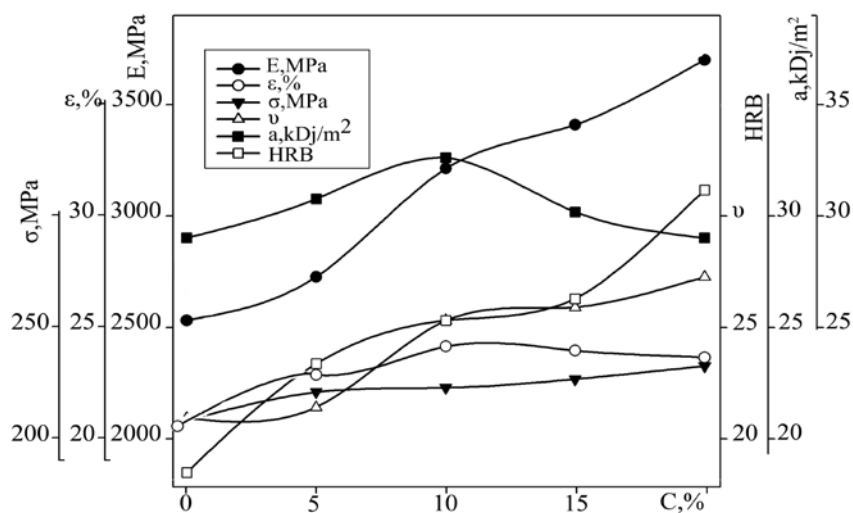


Fig.2. The influence of the sulfone-T fiber content on the strength characteristics of organoplastics based on it, where: E, MPa - modulus of elasticity or Young's modulus; ε, % - elongation at compression; σ, MPa - Compressive yield strength; ν - Poisson's ratio; a, kJ / m² - toughness; HRB - Brinell hardness

Along with the induced applied load, the destruction of brittle particles, the development of fracture along the interface between the matrix and the fiber contributes to the formation of microcracks or pores in the test samples. They are mainly formed in connection with the reorientation of the polymer molecules, and grow in a plane normal to the stress application axis. As the stress level increases, the pores grow more and finally coalesce to form a wide crack front [5], which reaches critical dimensions, accompanied by complete destruction for pure phenylone samples and samples with

a high degree of fiber filling with sulfon-T (15-20 wt. %) (Figures 3a, d, e).

The investigation of tribotechnical characteristics under conditions of dry friction at varying pressure values from 0.4 to 1.0 MPa allowed to establish that the optimum fiber concentration in the polymer matrix is 10 wt. %, over the entire range of loads studied. Compared with pure phenylone, an increase in wear resistance of 1.6 times was observed, with a simultaneous decrease in the coefficient of friction by 60% (Fig. 4).

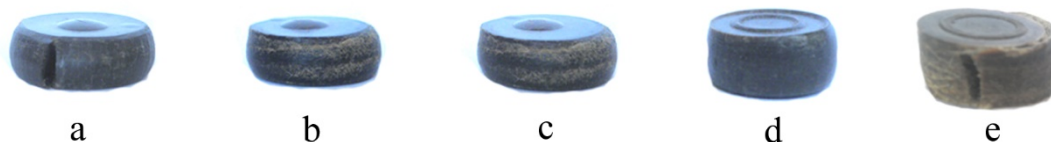


Fig. 3. Nature of destruction of samples of phenylone (a) and organoplastic based on it, containing 5 (b); 10 (c); 15 (d) 20 (e) wt. % Fiber after compression test

As for the microanalysis of the tribosurface, as a result of abrasion of the phenylone over ground steel under conditions of room temperature, a surface with apparent gouging paths is formed (Fig. 5a). Organoplastics are characterized by a pseudoelastic mechanism of abrasion [6]. This is testified to by shots of the microstructure of organoplastics surface (with a content of 10 wt% fiber), which

becomes specular, traces of the tracks from the introduction of roughness of the metal counterweave are hardly visible, fiber breakage from the surface was practically not observed (Figure 5b), which characterizes the strong adhesion bonds of components in organoplastics.

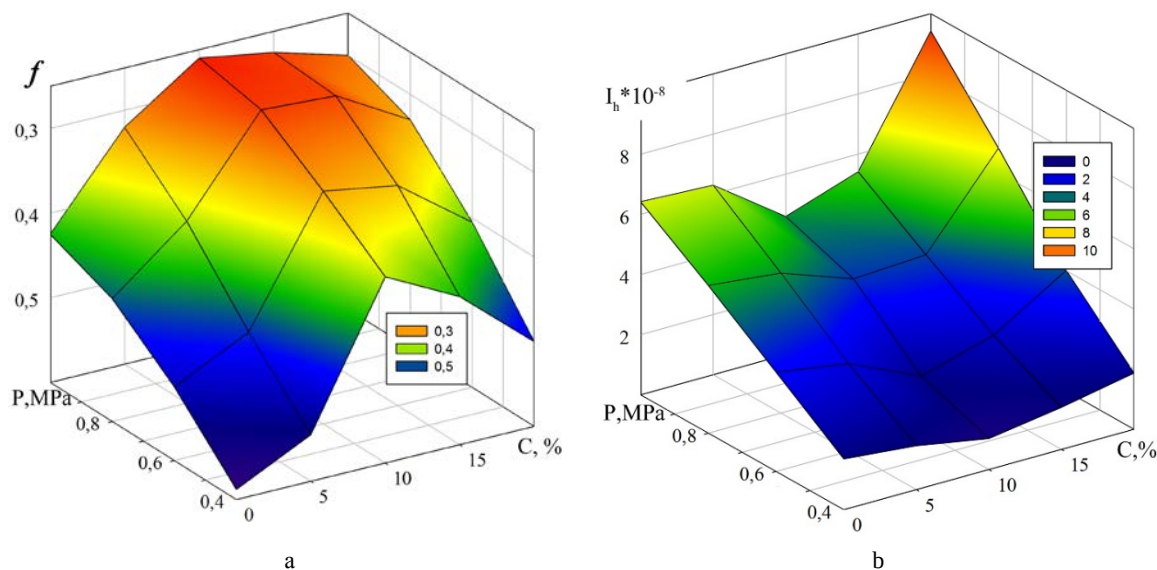


Fig. 4. Dependence of the coefficient of friction (a) and wear intensity (b) of phenylone and organoplastics on its basis on the influence of the load and the content of sulfone-T fiber in the polymer matrix

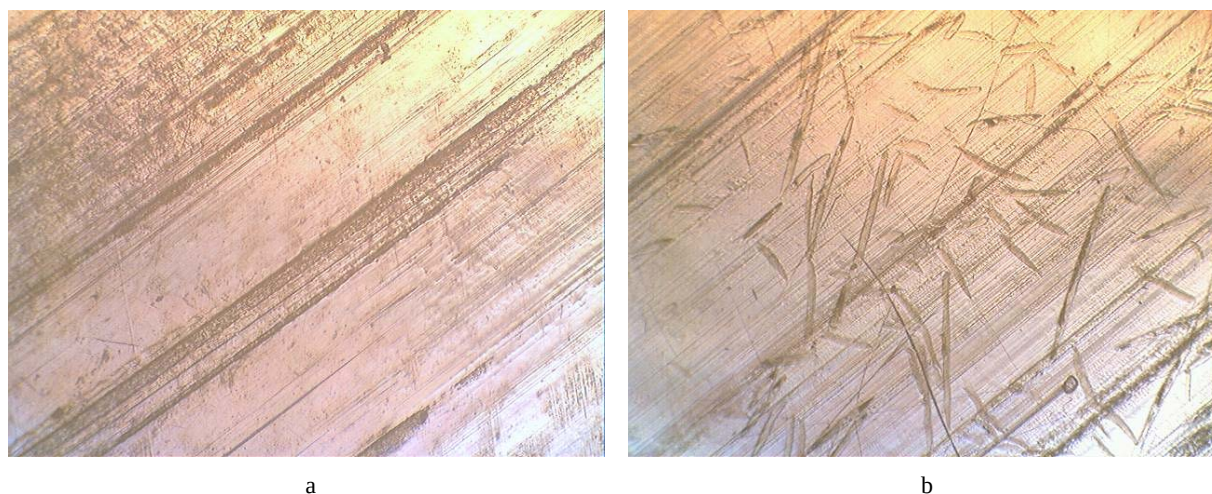


Fig. 5. Microstructure of the friction surface of phenylone (a) and organoplastics (b), with an increase of $\times 200$

Based on the positive results of laboratory studies, the replacement of the roller bearing of pins No. 6-7409a, mounted on the cradle of the axial-plunger pump NP-90, the sliding bearings made of organoplastic based on aromatic polyamide phenylene reinforced with discrete chemical fiber sulfone-T was proposed. The experimental bearing includes an outer steel ring (Figures 6, 3) and an inner conical ring (Figure 6, 2) made of organoplastic. The cone of conjugated surfaces is $200 \pm 5^\circ$. The outer steel rings of the

bearings are pressed into the mounting holes of the tube, while the inner ones, made of organoplastics, are pressed onto the journal (Fig. 6, 1), which is installed in the pump housing holes [7]. This replacement leads to an increase in the working resource by 3 - 4 times in comparison with the serial ones, which makes it possible to recommend details from organoplastics for use in hydrostatic transmissions of GST-90 (112) in pumps NP-90.

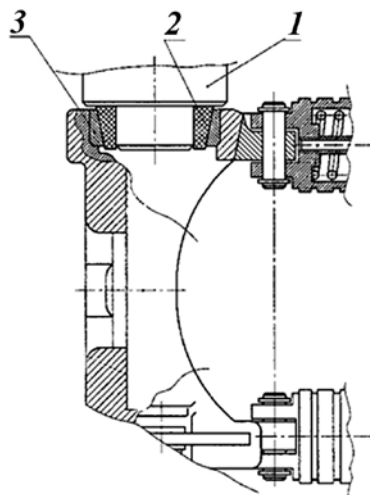


Fig. 6. General view of roller bearings of pins No. 6-7409a mounted on the cradle of the axial-plunger pump NP-90, where 1 - the outer steel ring; 2 - internal conical ring of organoplastics; 3 - outer steel ring

6. Conclusion

Thus, during the research of new polymer composite materials, it has been established that the reinforcement of aromatic polyamide phenylene with an organic discrete sulfone-T fiber leads to an increase in its strength characteristics, namely hardness, elastic modulus and Poisson's ratio by 1.7; 1.9 and 1.3 times, respectively; a significant increase in wear resistance (by 1.6 times) and a decrease in the coefficient of friction (by 60%). Experimental details from organoplastics were tested as an internal conical ring instead of a roller bearing of pins No. 6-7409a mounted on the cradle of the axial-plunger pump NP-90, which led to an increase in the working life.

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