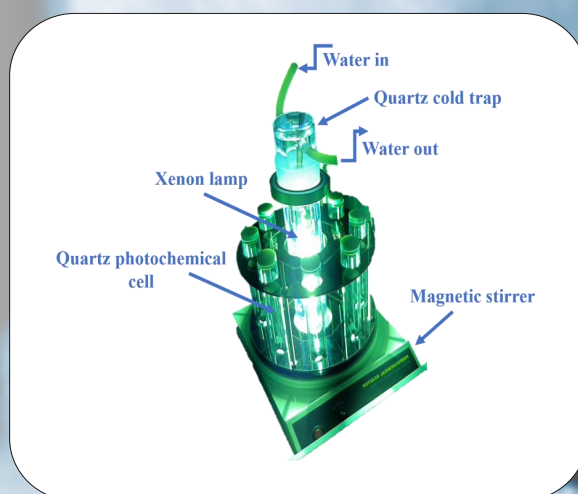


International journal
for science, technics and
innovations for the industry



MACHINES
TECHNOLOGIES
MATERIALS

YEAR XVII **Issue 1** / 2023 **ISSN PRINT 1313-0226**
ISSN WEB 1314-507X



Published by
Scientific technical
Union of Mechanical Engineering



MACHINES. TECHNOLOGIES. MATERIALS

INTERNATIONAL SCIENTIFIC JOURNAL

ISSN PRINT 1313-0226, ISSN WEB 1314-507X, YEAR XVII, ISSUE 1 / 2023

INTERNATIONAL EDITORIAL BOARD

EDITOR IN CHIEF:

Georgi Popov

Technical University of Sofia

BG

MEMBERS:

Abdrakhman Naizabekov

Rudny industrial institute

KZ

Ahmet H. Ertas

Bursa Technical University

TR

Albert Albers

Karlsruhe Institut of Technology

DE

Andrzej Golabczak

Lodz University of Technology

PL

Andrzej Huczko

Warsaw University

PL

Dimitar Karaivanov

University of Chemical Technology and Metallurgy, Sofia

BG

Dobre Runchev

Ss. Cyril and Methodius University in Skopje

NM

Emilia Abadjieva

Akita University

JP

Erdem Camurlu

Akdeniz University, Antalya

TR

Eugen Sheregii

University of Rzeszow

PL

Franz Haas

Graz University of Technology

AT

Galina Nicolcheva

Technical University of Sofia

BG

Gennadii Bagliuk

Institute for Problems of Materials Science NAS of Ukraine, Kiev

UA

Georgii Raab

Ufa State Aviation Technical University

RU

Gregory Gurevich

Shamoon College of Engineering, Ashdod

IL

Hiroiyuki Moriyama

Tokai University, Hiratsuka

JP

Idilia Batchkova

University of Chemical Technology and Metallurgy, Sofia

BG

Ivan Kralov

Technical University of Sofia

BG

Ivan Kuric

University of Zilina

SK

Julietta Kaleicheva

Technical University of Sofia

BG

Katia Vutova

Institute of Electronics, Bulgarian Academy of Sciences

BG

Maria Nikolova

Angel Kanchev University of Ruse

BG

Natasa Naprstkova

Jan Evangelista Purkyne University in Usti nad Labem

CZ

Oana Dodun

Gheorghe Asachi Technical University of Iasi

RO

Ognyan Andreev

Technical University of Sofia

BG

Predrag Dasic

High Technical Mechanical School of Trstenik

RS

Rasa Kandrotaitė

Kaunas University of Technology

LT

Raul Turmanidze

Georgian Technical University, Tbilisi

GE

Roumen Petrov

Ghent University

BE

Sergey Dobatkin

National University of Science and Technology "MISIS", Moscow

RU

Souren Mitra

Jadavpur University, Kolkata

IN

Svetlana Gubenko

National Metallurgical Academy of Ukraine, Dnipro

UA

Vedran Mrzljak

University of Rijeka

HR

Wu Kaiming

Wuhan University of Science and Technology

CN

TECHNICAL EDITORS:

M. Sc. Eng. Radoslav Daskalov, M. Sc. Eng. Oleg Mihailov

Scientific and technical union of mechanical engineering

108 R. S. Rakovski str., Sofia, Bulgaria

www.stumejournals.com, office@stumejournals.com

CONTENTS

MACHINES

The influence of steam extractions operation dynamics on the turbine efficiencies and losses Mrzljak Vedran, Prpić-Oršić Jasna, Glučina Matko, Poljak Igor	3
CFD simulation of airflow through the throttle body of the air intake system applied to the Formula Student vehicle Marko Lučić	7
The prospects for the use of liquefied gas in maritime transport Romanov Topuria, Mikheil Lezhava, Zaza Shubladze, Jemal Sharadze	12
Improving wellbore stability by applying drilling mud with Fe₂O₃ nanoparticles Petar Mijić, Igor Medved, Bojan Kuhar, Petra Matešković, Marcela Vargić, Domagoj Mrnjavčić, Karlo Findri ...	14

TECHNOLOGIES

Study of the radial shear rolling effect on the gradient microstructure formation in technical titanium and mechanical properties changes Abdrakhman Naizabekov, Irina Volokitina, Alexandr Arbuz, Andrey Tolkushkin, Darkhan Nurakhmetov	18
Welding technology of martensitic steel P91 and austenitic steel 304H – State of the art Aleksandra Krstevska, Dobro Runchev, Filip Zdraveski	21
Visualization and analysis of gear drives parameters with the help of computer-aided mathematics systems Svetlin Stoyanov	24
Basic Analytical and Geometric Synthesis of Conic Convolute Helical Surfaces of Spatial Rack Drives. Software and Graphic Study Emilia Abadjieva	28
Design for Sustainability: A Review Jelena Djokikj, Elisaveta Doncheva	35

MATERIALS

Eco-inspired synthesis and photocatalytic application of novel ZnO nanoparticles from peel extract of banana Daniela Šojić Merkulov, Sabolč Bognar, Nina Finčur, Dušica Jovanović	38
Effect of solanine on corrosion of steel 3 in lactic acid Tamara Pyzhik, Tatyana Povshok, Valery Sarokin, Angel Velikov	40
Complex electrical impedance and dielectric spectroscopy studies of BaTiO₃- BaSnO₃ ceramics obtained via sol-gel method. Mihaela Aleksandrova, Lyuben Lakov, Yordan Marinov, Vladimir Petkov, Bojidar Jivov, Geordi Hadjichristov	43
Study of aluminum content on the structure and phase composition of synthesized aluminum-matrix composites Yevheniia Kyryliuk, Genadii Bagliuk, Stepan Kyryliuk, Bykov Oleksandr, Yulia Shishkina	46

The influence of steam extractions operation dynamics on the turbine efficiencies and losses

Mrzljak Vedran¹, Prpić-Oršić Jasna¹, Glučina Matko², Poljak Igor³

¹Faculty of Engineering, University of Rijeka, Vukovarska 58, 51000 Rijeka, Croatia

²University of Rijeka, Trg braće Mažuranića 10, 51000 Rijeka, Croatia

³Department of maritime sciences, University of Zadar, Mihovila Pavlinovića 1, 23000 Zadar, Croatia

E-mail: vedran.mrzljak@riteh.hr, jasna.prpic-orsic@riteh.hr, matko.glucina@uniri.hr, ipoljak1@unizd.hr

Abstract: In this paper are presented results of a low-pressure steam turbine energy and exergy analysis during turbine extractions opening/closing. All possible combinations of extractions opening/closing are observed. The highest mechanical power which can be produced by this turbine (when all steam extractions are closed) is 28017.48 kW in real and 31988.20 kW in an ideal situation. For all observed steam extractions opening/closing combinations is obtained that energy efficiency and energy losses range is relatively small (from 87.56% to 87.94% for energy efficiency and from 3360.46 kW to 3970.72 kW for energy losses). Trends in energy and exergy losses (destructions) are identical for all observed extractions opening/closing combinations. Analyzed turbine efficiencies (both energy and exergy) will decrease for a maximum 1% during the steam extractions closing. Turbine steam extractions closing decrease turbine efficiencies and increases turbine losses (destructions), what is valid from both energy and exergy aspects.

KEYWORDS: STEAM TURBINE, STEAM EXTRACTIONS, OPERATION DYNAMICS, EFFICIENCY, LOSSES

1. Introduction

A variety of steam turbines can be found in the power plants worldwide. Main steam turbines are usually complex steam turbines which consist of several cylinders connected to the same shaft [1, 2]. Auxiliary steam turbines are usually used for the additional mechanical power producing or for a direct drive of various mechanical power consumers [3, 4].

It should be highlighted that nowadays, steam turbine is not the mechanical power producer only, it is also a machine for steam delivery (heat energy delivery) to various heaters inside the power plant [5, 6]. Steam delivery to the heaters is performed through steam turbine extractions. Complex multi-cylinder steam turbines usually have few steam extractions from each cylinder [7, 8], while auxiliary steam turbines usually did not have any steam extraction [9]. Therefore, steam extractions are essential part of recent steam turbines and they can notably influence steam turbine performance.

Steam turbine performance during various extractions operation dynamics can be investigated by using several possible techniques – two of such techniques are energy and exergy analyses [10, 11], which are applied in this paper.

In this paper is performed analysis of low-pressure steam turbine developed power, energy and exergy efficiencies as well as losses for each possible steam extractions opening/closing combination. Steam extractions closing will surely increase turbine developed power, but it is interesting to observe what will happen with turbine efficiencies and losses in such operating regimes.

2. Description of the analyzed steam turbine

Scheme of the analyzed low-pressure steam turbine along with operating points required for the analyses, is presented in Fig. 1.

Low-pressure turbine analyzed in this paper is the last cylinder of a complex, two cylinder steam turbine. Both cylinders (high-pressure and low-pressure cylinder) are connected to the same shaft which drives an electric generator. Between mentioned cylinders is mounted re-heater. Details related to the whole described turbine and power plant in which it operates can be found in [12].

Steam re-heater delivers superheated steam to the analyzed low-pressure turbine. The turbine has four steam extractions (operating points 2, 3, 4 and 5) which are used for steam delivery to the components of low-pressure feed water heating system (deaerator and low-pressure feed water heaters) [13]. The remaining steam mass flow rate, which expand through all the stages of the observed turbine, is finally delivered to steam condenser for condensation [14].

The observed steam turbine is analyzed as an independent component (the influences of steam extractions opening/closing on other power plant components or on the entire steam power plant are not considered). Due to simplicity, it is considered that each steam turbine extraction can be fully opened or fully closed (partially opened extractions are not observed).

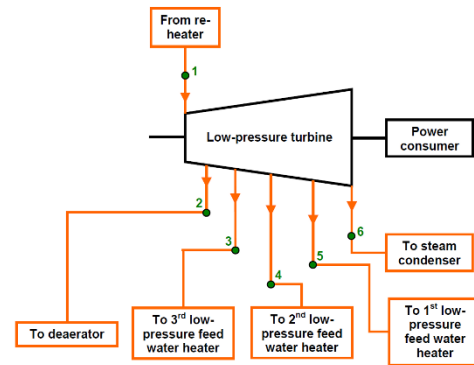


Fig. 1. Scheme and marked operating points of the analyzed low-pressure steam turbine

Ideal (isentropic) and real (polytropic) steam expansion processes through the analyzed turbine are shown in Fig. 2 (operating points are in accordance to Fig. 1). Real (polytropic) steam expansion process is marked with numbers from 1 to 6, while ideal (isentropic) expansion is marked with numbers from 1 to 6i. Ideal (isentropic) process assumes that steam specific entropy remains constant during expansion [15]. Steam extractions are marked with red arrows (operating points 2, 3, 4 and 5).

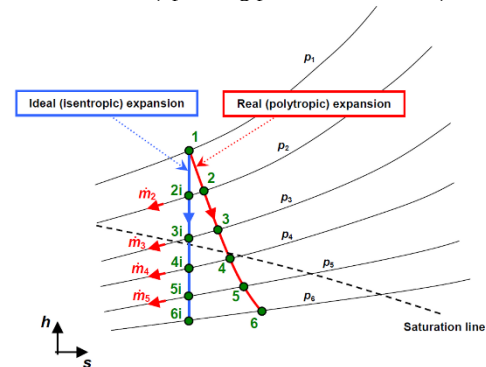


Fig. 2. Steam real (polytropic) and ideal (isentropic) expansion processes through the analyzed turbine in h-s diagram

3. Equations for the low-pressure steam turbine energy and exergy analysis

3.1. General energy and exergy equations and balances

The main energy and exergy balance equations are [16]:

$$\dot{Q}_{in} + P_{in} + \sum \dot{E}n_{in} = \dot{Q}_{out} + P_{out} + \sum \dot{E}n_{out} + \dot{E}n_L, \quad (1)$$

$$\dot{X}_{in} + P_{in} + \sum \dot{E}x_{in} = \dot{X}_{out} + P_{out} + \sum \dot{E}x_{out} + \dot{E}x_L, \quad (2)$$

where $\dot{Q}$ and $\dot{X}$ are heat energy and exergy transfer, P is mechanical power, index in is related to the inlet (input), index out is related to outlet (output) and index L is related to the loss (energy or exergy). $\dot{E}n$ and $\dot{E}x$ are total energy and exergy flow of any fluid stream which can be calculated as [17]:

$$\dot{E}n = \dot{m} \cdot h, \quad (3)$$

$$\dot{E}x = \dot{m} \cdot \varepsilon, \quad (4)$$

where $\dot{m}$ is mass flow rate, h is specific enthalpy and ε is specific exergy. Always valid mass flow rate balance is:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out}, \quad (5)$$

while overall energy and exergy efficiency equation can be presented as [18]:

$$\eta_{en(ex)} = \frac{\text{cumulative energy (exergy) output}}{\text{cumulative energy (exergy) input}}. \quad (6)$$

3.2. Equations for the energy and exergy analysis of the observed low-pressure steam turbine

Equations for the energy and exergy analyses of the investigated low-pressure steam turbine are presented in this subsection for a situation when all of the steam extractions are open. Equations for the turbine energy and exergy analyses when one or more steam extractions are closed will be defined by using the same equations (mass flow rate through closed extraction is equal to zero).

Equations for the low-pressure steam turbine energy analysis (all steam extractions open), according to Fig. 1 and Fig. 2, are:

- Turbine real (polytropic) mechanical power:

$$P_{re} = \dot{m}_1 \cdot (h_1 - h_2) + (\dot{m}_1 - \dot{m}_2) \cdot (h_2 - h_3) + (\dot{m}_1 - \dot{m}_2 - \dot{m}_3) \cdot (h_3 - h_4) + (\dot{m}_1 - \dot{m}_2 - \dot{m}_3 - \dot{m}_4) \cdot (h_4 - h_5) + (\dot{m}_1 - \dot{m}_2 - \dot{m}_3 - \dot{m}_4 - \dot{m}_5) \cdot (h_5 - h_6). \quad (7)$$

- Turbine ideal (isentropic) mechanical power:

$$P_{id} = \dot{m}_1 \cdot (h_1 - h_{2i}) + (\dot{m}_1 - \dot{m}_2) \cdot (h_{2i} - h_{3i}) + (\dot{m}_1 - \dot{m}_2 - \dot{m}_3) \cdot (h_{3i} - h_{4i}) + (\dot{m}_1 - \dot{m}_2 - \dot{m}_3 - \dot{m}_4) \cdot (h_{4i} - h_{5i}) + (\dot{m}_1 - \dot{m}_2 - \dot{m}_3 - \dot{m}_4 - \dot{m}_5) \cdot (h_{5i} - h_{6i}). \quad (8)$$

- Turbine energy loss (energy destruction):

$$\dot{E}n_L = P_{id} - P_{re}. \quad (9)$$

- Turbine energy efficiency:

$$\eta_{en} = \frac{P_{re}}{P_{id}}. \quad (10)$$

Exergy analysis depends on the ambient conditions. The ambient conditions (dead state conditions) in this analysis are: pressure of 1 bar and a temperature of 25 °C. For the steam turbine exergy analysis, the relevant turbine mechanical power is real (polytropic) power, calculated by Eq. 7 for the situation when all steam extractions are open. Equations for the exergy analysis of investigated low-pressure steam turbine with all steam extractions open, Fig. 1, are:

- Turbine exergy inlet (input):

$$\dot{E}x_{in} = \dot{m}_1 \cdot \varepsilon_1. \quad (11)$$

- Turbine exergy outlet (output):

$$\dot{E}x_{out} = \dot{m}_2 \cdot \varepsilon_2 + \dot{m}_3 \cdot \varepsilon_3 + \dot{m}_4 \cdot \varepsilon_4 + \dot{m}_5 \cdot \varepsilon_5 + \dot{m}_6 \cdot \varepsilon_6 + P_{re}. \quad (12)$$

- Turbine exergy loss (exergy destruction):

$$\dot{E}x_L = \dot{E}x_{in} - \dot{E}x_{out}. \quad (13)$$

- Turbine exergy efficiency:

$$\eta_{ex} = \frac{P_{re}}{\dot{E}x_{in} - \dot{E}x_{out} + P_{re}}. \quad (14)$$

All equations for the analyzed turbine during one or more steam extractions closing remains the same as presented above, from Eq. 7 to Eq. 14. The closing of one or more steam turbine extractions means that steam mass flow rate through closed steam extraction is equal to zero. All other steam operating parameters remain the same as in the situation when all steam turbine extractions are open. The calculation principle is always the same, regardless of observed steam turbine extractions opening/closing combination.

4. Steam operating parameters required for low-pressure steam turbine energy and exergy analysis

Each fluid flow stream operating parameters (in each operating point from Fig. 1) measured in the power plant are found in [12]. Using measured operating parameters, all the others, required for the energy and exergy analyses are calculated with NIST-Refprop 9.0 software [19]. Steam operating parameters in each operating point from Fig. 1 and Fig. 2 are presented in Table 1 for real (polytropic) expansion process and in Table 2 for ideal (isentropic) process. It should be highlighted that ideal expansion process is a process between the same pressures and it uses the same mass flow rates as the real (polytropic) process, but in ideal process steam specific entropy remains always constant, as at the turbine inlet.

Table 1. Steam operating parameters in each operating point of the analyzed turbine – real (polytropic) steam expansion

O.P.	Temperature (°C)	Pressure (bar)	Mass flow rate (kg/s)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kg·K)	Specific exergy (kJ/kg)
1	371.000	17.090	33.200	3187.0	7.1065	1072.8
2	279.153	7.980	3.170	3012.8	7.1574	883.4
3	165.472	2.730	1.790	2796.0	7.2027	653.1
4	98.456	0.960	1.570	2625.4	7.2442	470.1
5	68.301	0.290	1.240	2455.8	7.2892	287.1
6	41.490	0.080	25.430	2343.1	7.4868	115.4

O.P. = Operating point (refers to Fig. 1.)

Table 2. Steam operating parameters in each operating point of the analyzed turbine – ideal (isentropic) steam expansion

O.P.	Pressure (bar)	Mass flow rate (kg/s)	Isentropic specific enthalpy (kJ/kg)	Isentropic specific entropy (kJ/kg·K)
1	17.090	33.200	3187.0	7.1065
2i	7.980	3.170	2985.1	7.1065
3i	2.730	1.790	2754.8	7.1065
4i	0.960	1.570	2574.3	7.1065
5i	0.290	1.240	2393.5	7.1065
6i	0.080	25.430	2223.5	7.1065

O.P. = Operating point (refers to Fig. 2.)

Steam operating parameters in each analyzed turbine operating point found in [12] were presented in a situation when all steam extractions are open. Steam extractions closing do not affect steam operating parameters, they remain the same as presented in Table 1 and Table 2 (only the steam mass flow rate is set to zero for any closed extraction).

The analyzed low-pressure steam turbine has four steam extractions (operating points 2, 3, 4 and 5, Fig. 1). All possible combinations of the steam extractions opening/closing are presented in Table 3. Turbine operating parameters were investigated for each possible combination.

From Table 3 can be seen that the first combination is when all steam turbine extractions are open while the last combination is when all steam turbine extractions are closed. There are four possible combinations when one turbine extraction is closed and all the others are open (combinations from 2 to 5, Table 3) and six possible combinations when two turbine extractions are open and two are closed (combinations from 6 to 11, Table 3). Finally, there are four possible combinations when three steam extractions are closed with only one open (combinations from 12 to 15, Table 3).

Table 3. Steam extractions opening/closing combinations

Steam extractions combination number	Steam extractions* (2-3-4-5)
1	O-O-O-O
2	C-O-O-O
3	O-C-O-O
4	O-O-C-O
5	O-O-O-C
6	C-C-O-O
7	O-C-C-O
8	O-O-C-C
9	C-O-C-O
10	C-O-O-C
11	O-C-O-C
12	C-C-C-O
13	O-C-C-C
14	C-O-C-C
15	C-C-O-C
16	C-C-C-C

* o = extraction open; c = extraction closed

5. The results of the low-pressure steam turbine energy and exergy analysis during steam extractions opening/closing

The change in real (polytropic) and ideal (isentropic) turbine mechanical power during steam extractions opening/closing is presented in Fig. 3. It is evident that trends in both ideal and real power are identical and that ideal power is higher than the real one, regardless of the observed combination (because the ideal power did not consider losses which occur during steam expansion).

As can be expected, combination 1 when all steam extractions are open resulted with the lowest mechanical power, while combination 16 which represents all closed steam extractions resulted with the highest produced mechanical power (both ideal and real). The highest mechanical power which can be produced by this turbine (all steam extractions closed) is 28017.48 kW in real and 31988.20 kW in an ideal situation. If only one steam extraction is closed (combinations from 2 to 5), the highest produced mechanical power is observed when the first steam extraction is closed (combination 2). In the situation of two closed extractions (combinations from 6 to 11), the highest power is obtained when first two extractions are closed (combination 6). Finally, the highest power is obtained in combination 12 when first three extractions are closed.

From Fig. 3 can be concluded that closing the steam extractions which are the closest to the turbine inlet has a notable effect on the increase in turbine power because more steam will expand through the turbine and more mechanical power will be produced.

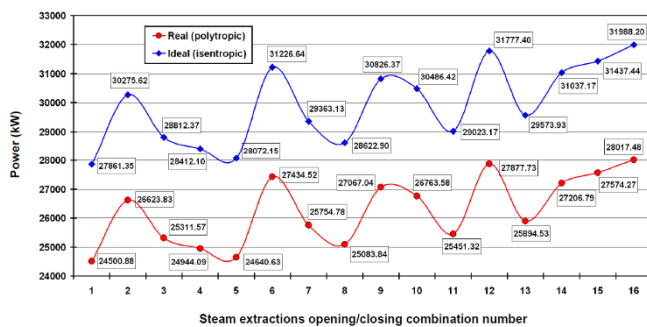


Fig. 3. Change in real (polytropic) and ideal (isentropic) power during turbine extractions opening/closing

The influence of steam extractions opening/closing on the observed low-pressure turbine energy efficiencies and energy losses is presented in Fig. 4. The highest energy efficiency and the lowest turbine energy loss can be seen when all steam extractions are open (combination 1), while one of the lowest turbine energy efficiency and the highest energy loss is observed in a situation when all steam extractions are closed (Combination 16). For all observed steam extractions opening/closing combinations, it can be concluded that

energy efficiency and energy loss range is relatively small (from 87.56% to 87.94% for energy efficiency and from 3360.46 kW to 3970.72 kW for energy loss).

Final conclusion which can be derived from Fig. 3 and Fig. 4 is that steam extractions closing increases produced mechanical power and energy losses, while simultaneously decreases turbine energy efficiency.

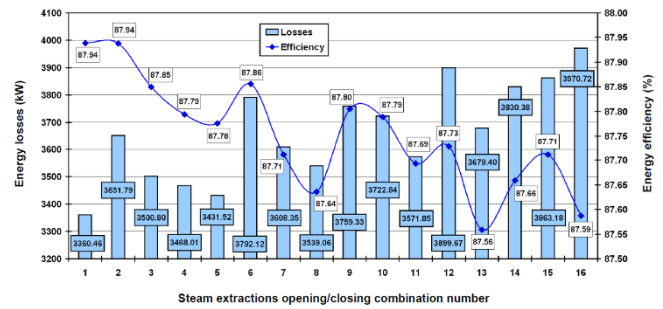


Fig. 4. Change in energy losses and energy efficiencies during turbine extractions opening/closing

Exergy input of the observed turbine is always the same (equal to 35616.96 kW), regardless of the observed extractions opening/closing combination. However, turbine exergy output is changing for the observed extractions opening/closing combinations, as presented in Fig. 5. The highest turbine exergy output equal to 32498.99 kW can be observed in combination 1 (all extractions opened), while the lowest turbine exergy output equal to 31848.76 kW is obtained in combination 16 (all extractions closed). From Fig. 5 can also be observed that steam extractions closing from the turbine inlet to the turbine outlet reduce exergy output.

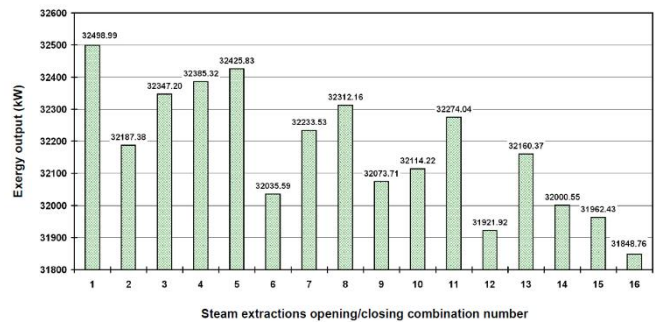


Fig. 5. Change in exergy output during turbine extractions opening/closing

Change in exergy loss (exergy destruction) and exergy efficiency of the observed low-pressure steam turbine during extractions opening/closing is presented in Fig. 6.

Comparison of turbine energy losses (energy destructions), Fig. 4, and turbine exergy losses (exergy destructions), Fig. 6, shows that the trends in losses are identical for all observed extractions opening/closing combinations. Exergy efficiencies show slightly different trends in comparison to energy efficiencies. However, the dominant conclusion is valid regardless of the observed analysis – steam extractions closing decreases turbine efficiencies and increases turbine losses (destructions).

For the observed extractions opening/closing combinations, turbine exergy efficiency range is between 88.71% and 88.14%. It can be concluded that observed turbine efficiencies (both energy and exergy) will decrease for a maximum 1% during the steam extractions closing.

Further analysis related to the observed low-pressure steam turbine and steam extractions opening/closing combinations will be based on various Artificial Intelligence (AI) methods and processes [20-22]. The aim will be to find optimal steam extractions opening/closing combination (along with partially opened extractions) to perform the complete optimization of the observed steam turbine.

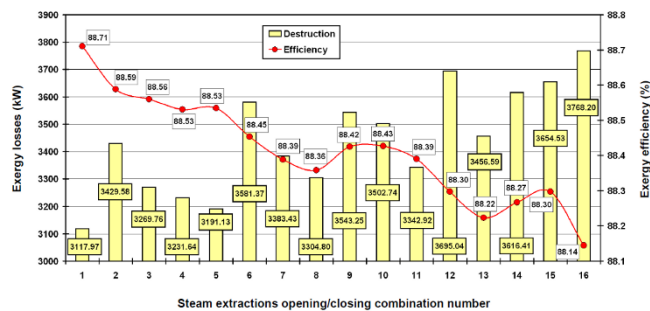


Fig. 6. Change in exergy losses and exergy efficiencies during turbine extractions opening/closing

6. Conclusions

This paper presents energy and exergy analysis results of a low-pressure steam turbine during its extractions opening/closing. It is observed all possible combinations of extractions opening/closing, with whole mass flow rates (partial mass flow rates were not observed). The most important obtained conclusions are:

- The highest mechanical power which can be produced by this turbine (when all steam extractions are closed) is 28017.48 kW in real and 31988.20 kW in an ideal situation.
- Closing the steam extractions which are the closest to the turbine inlet has a notable effect on the increase in turbine power because more steam will expand through the turbine and more mechanical power will be produced.
- For all observed steam extractions opening/closing combinations is obtained that energy efficiency and energy losses range is relatively small (from 87.56% to 87.94% for energy efficiency and from 3360.46 kW to 3970.72 kW for energy losses).
- Trends in energy and exergy losses (destructions) are identical for all observed extractions opening/closing combinations.
- Observed turbine efficiencies (both energy and exergy) will decrease for a maximum 1% during the steam extractions closing.
- Steam extractions closing decreases turbine efficiencies and increases turbine losses (destructions), what is valid from both energy and exergy aspects.

7. Acknowledgment

This research has been supported by the Croatian Science Foundation under the project IP-2018-01-3739, University of Rijeka scientific grant uniri-tehnic-18-18-1146 and University of Rijeka scientific grant uniri-tehnic-18-14.

8. References

[1] Guo, J. Q., Li, M. J., Xu, J. L., Yan, J. J., & Ma, T. (2020). Energy, exergy and economic (3E) evaluation and conceptual design of the 1000 MW coal-fired power plants integrated with S-CO₂ Brayton cycles. *Energy Conversion and Management*, 211, 112713. (doi:10.1016/j.enconman.2020.112713)

[2] Bolatturk, A., Koskun, A., & Geredelioglu, C. (2015). Thermodynamic and exergoeconomic analysis of Çayırhan thermal power plant. *Energy conversion and management*, 101, 371-378. (doi:10.1016/j.enconman.2015.05.072)

[3] Mrzljak, V., Senčić, T., & Žarković, B. (2018). Turbogenerator steam turbine variation in developed power: Analysis of exergy efficiency and exergy destruction change. *Modelling and Simulation in Engineering*, 2018. (doi:10.1155/2018/2945325)

[4] Mrzljak, V., Poljak, I., & Mrakovčić, T. (2017). Energy and exergy analysis of the turbo-generators and steam turbine for the main feed water pump drive on LNG carrier. *Energy conversion and management*, 140, 307-323. (doi:10.1016/j.enconman.2017.03.007)

[5] Nikam, K. C., Kumar, R., & Jilte, R. (2020). Exergy and exergo-environmental analysis of a 660 MW supercritical coal-fired power plant. *Journal of Thermal Analysis and Calorimetry*, 1-14. (doi:10.1007/s10973-020-10268-y)

[6] Naserbegi, A., Aghaie, M., Minucmehr, A., & Alahyarizadeh, G. (2018). A novel exergy optimization of Bushehr nuclear power plant by gravitational search algorithm (GSA). *Energy*, 148, 373-385. (doi:10.1016/j.energy.2018.01.119)

[7] Nikam, K. C., Kumar, R., & Jilte, R. (2020). Economic and exergoeconomic investigation of 660 MW coal-fired power plant. *Journal of Thermal Analysis and Calorimetry*, 1-15. (doi:10.1007/s10973-020-10213-z)

[8] Kopac, M., & Hilalci, A. (2007). Effect of ambient temperature on the efficiency of the regenerative and reheat Çatalağzı power plant in Turkey. *Applied Thermal Engineering*, 27(8-9), 1377-1385. (doi:10.1016/j.applthermaleng.2006.10.029)

[9] Mrzljak, V., Prpić-Oršić, J., & Poljak, I. (2018). Energy power losses and efficiency of low power steam turbine for the main feed water pump drive in the marine steam propulsion system. *Pomorski zbornik*, 54(1), 37-51. (doi:10.18048/2018.54.03)

[10] Mrzljak, V., & Poljak, I. (2019). Energy analysis of main propulsion steam turbine from conventional LNG carrier at three different loads. *NAŠE MORE: znanstveni časopis za more i pomorstvo*, 66(1), 10-18. (doi:10.17818/NM/2019/1.2)

[11] Anđelić, N., Mrzljak, V., Lorencin, I., & Baressi Šegota, S. (2020). Comparison of Exergy and Various Energy Analysis Methods for a Main Marine Steam Turbine at Different Loads. *Pomorski zbornik*, 59(1), 9-34. (doi:10.18048/2020.59.01)

[12] Vakilabadi, M. A., Bidi, M., & Najafi, A. F. (2018). Energy, Exergy analysis and optimization of solar thermal power plant with adding heat and water recovery system. *Energy conversion and management*, 171, 1639-1650. (doi:10.1016/j.enconman.2018.06.094)

[13] Mrzljak, V., Poljak, I., & Medica-Viola, V. (2016). Efficiency and losses analysis of low-pressure feed water heater in steam propulsion system during ship maneuvering period. *Pomorstvo*, 30(2), 133-140. (doi:10.31217/p.30.2.6)

[14] Medica-Viola, V., Pavković, B., & Mrzljak, V. (2018). Numerical model for on-condition monitoring of condenser in coal-fired power plants. *International Journal of Heat and Mass Transfer*, 117, 912-923. (doi:10.1016/j.ijheatmasstransfer.2017.10.047)

[15] Medica-Viola, V., Baressi Šegota, S., Mrzljak, V., & Stifanić, D. (2020). Comparison of conventional and heat balance based energy analyses of steam turbine. *Pomorstvo*, 34(1), 74-85. (doi:10.31217/p.34.1.9)

[16] Aljundi, I. H. (2009). Energy and exergy analysis of a steam power plant in Jordan. *Applied thermal engineering*, 29(2-3), 324-328. (doi:10.1016/j.applthermaleng.2008.02.029)

[17] Mrzljak, V., Poljak, I., & Medica-Viola, V. (2017). Dual fuel consumption and efficiency of marine steam generators for the propulsion of LNG carrier. *Applied Thermal Engineering*, 119, 331-346. (doi:10.1016/j.applthermaleng.2017.03.078)

[18] Kanoğlu, M., Çengel, Y. A., & Dinçer, İ. (2012). Efficiency evaluation of energy systems. *Springer Science & Business Media*.

[19] Lemmon, E. W., Huber, M. L., & McLinden, M. O. (2010). NIST Standard Reference Database 23, Reference Fluid Thermodynamic and Transport Properties (REFPROP), version 9.0, National Institute of Standards and Technology. R1234yf. fld file dated December, 22, 2010.

[20] Lorencin, I., Anđelić, N., Mrzljak, V., & Car, Z. (2019). Genetic algorithm approach to design of multi-layer perceptron for combined cycle power plant electrical power output estimation. *Energies*, 12(22), 4352. (doi:10.3390/en12224352)

[21] Mrzljak, V., Anđelić, N., Lorencin, I., & Sandi Baressi Šegota, S. (2021). The influence of various optimization algorithms on nuclear power plant steam turbine exergy efficiency and destruction. *Pomorstvo*, 35(1), 69-86. (doi:10.31217/p.35.1.8)

[22] Anđelić, N., Baressi Šegota, S., Lorencin, I., Poljak, I., Mrzljak, V., & Car, Z. (2021). Use of Genetic Programming for the Estimation of CODLAG Propulsion System Parameters. *Journal of Marine Science and Engineering*, 9(6), 612. (doi:10.3390/jmse9060612)

CFD simulation of airflow through the throttle body of the air intake system applied to the Formula Student vehicle

Marko Lučić

Faculty of Mechanical Engineering, University of Montenegro, Podgorica, Montenegro

E-mail: markol@ucg.ac.me

Abstract: In this paper, a simulation of their flow through the throttle valve on the Formula Student vehicle was performed. The throttle valve is an element that, according to the regulations of the Formula Student competition, must be present in the intake installation of the vehicle's power unit if it is a competition in class IC. The correct design of the throttle is of great importance for the power unit to work properly, but also to extract the maximum performance of the power unit itself, and thus of the competition vehicle as a whole. One of the main tasks of the throttle is to allow air to flow with as little resistance as possible. For the CFD simulation in this work, ANSYS Fluent was used, which proved to be a very powerful tool in the CFD simulation of the throttle body.

Keywords: CFD, THROTTLE BODY, VEHICLE, IC ENGINES, FORMULA STUDENT

1. Introduction

The Formula Student competition is getting more and more popular. This competition is very attractive because it provides students with a good springboard for employment in the automotive industry after graduation. The number of Formula Student teams is growing year by year. Students from universities around the world compete to design a small racing vehicle. The design of the air intake system together with the throttle body applied to Formula Student vehicles is a very current topic, as evidenced by a large number of articles on the mentioned topic [1-8]. This work is structured into six chapters. The first chapter is an introduction and this chapter outlines what is covered in each of the six chapters. The second chapter is related to the design of the throttle body and the limitations prescribed by the organizers of the Formula Student competition. The CFD analysis of the throttle body was performed in chapter three, while the results of the CFD analysis were presented in chapter four. Chapter 5 is the conclusion on the topic of the work itself, and chapter six lists the references used in the work.

2. Formula Student throttle body

2.1. Throttle body

In the Formula Student competition, the big challenge is designing the intake system for the engine. As the Formula Student competition uses engines that are installed on motorcycles, it is necessary to modify them. The main modifications relate to the adjustment of the intake and exhaust installation, the engine map, as well as the cooling system itself, and the fuel system. The possibility of changing some structural parts of the engine, such as modification of the engine pistons, and crankshaft, should also be considered. To consider the possibility of modifying the crankshaft, it is necessary to perform a dynamic analysis of the forces acting in the engine, which is preceded by a kinematic analysis. An example of kinematic analysis is given in Ref. [9] in which this analysis can be done very easily using CATIA software.

Electronic Fuel Injection (EFI) is an active system that adjusts fuel delivery for the internal combustion engine, and the carburetor is a passive system that controls the intake of the fuel and air mixture. Fuel delivery to the engine is managed by the engine control unit (ECU), which precisely controls the duration and time of fuel delivery through fuel injectors. It can be said that the throttle body is an air valve. The throttle body has the task of allowing air to enter the engine. The more air delivered in combination with the appropriate amount of fuel, the more power is obtained from the engine, theoretically. This would mean that the use of a larger diameter throttle body also means a larger amount of airflow, which is not always the best move. The diameter of the throttle body must be of the appropriate size according to the volume of the engine. If the throttle body diameter is too large, the air velocity is slow, but more air is sucked into the engine, while if the diameter is too small, the air velocity is faster, but not enough air can pass. If a

forced-induction system is used, the diameter of the throttle body becomes less critical because the turbocharger or supercharger pushes air into the engine. A smaller throttle body can be used in a turbo setup because the air pressure and air density are approximately twice as high as in a naturally aspirated engine [10]. Figure 1 shows the barrel throttle body concept, which is very often used on Formula Student vehicles.



Fig. 1 Barrel Throttle Valve [11]

2.2. Throttle body restriction

Restrictions for the throttle body are given in the Formula Student Rulebook [12]. This regulation defines that the vehicle must be equipped with a throttle body, which can be of any size or design. The throttle must be activated by a mechanical foot pedal or rod system. Throttle position is defined as the percentage of time from fully closed 0% to open 100%. The mechanism of the throttle system must be protected from debris penetration to prevent jamming. Rulebook [12] defines two intake system configurations for naturally aspirated engines (Figure 2) and turbocharged or supercharged engines (Figure 3). Depending on which type of configuration is chosen, the position of the throttle body in the air intake system will also be defined. It is important to emphasize that in the case of using a turbocharged or supercharged configuration, a throttle body with a smaller diameter can be used compared to a configuration with naturally aspirated engines.

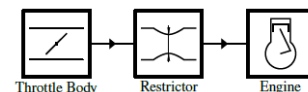


Fig 2. Configuration for naturally aspirated engines [12]

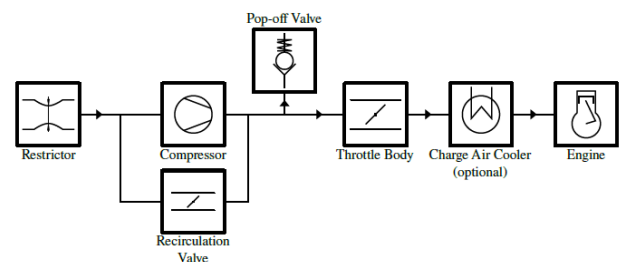


Fig 3. Configuration for turbocharged or supercharged engines [12]

3. CFD simulations of the throttle body

In this chapter, a CFD simulation of two throttle bodies was performed to see how the small geometrical difference between them affects the airflow. Figures 4 and 5 show two throttle bodies that were considered during the CFD simulation. Throttle body 2D geometries are shown in Figures 4 and 5. CFD simulation was performed for both throttle bodies at three characteristic positions, i.e. for positions of 50%, 75%, and 100% open throttle body. In Ansys Design Modeler

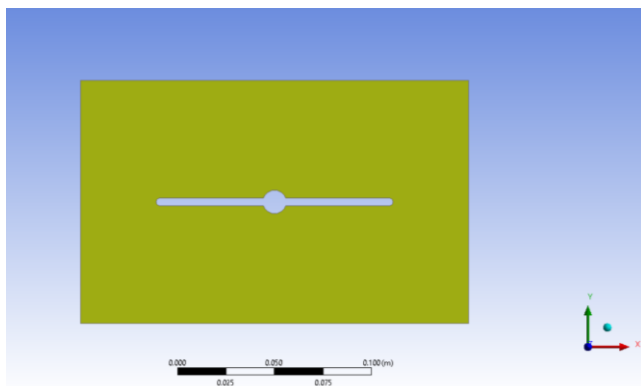


Fig 4. Throttle body (concept) A

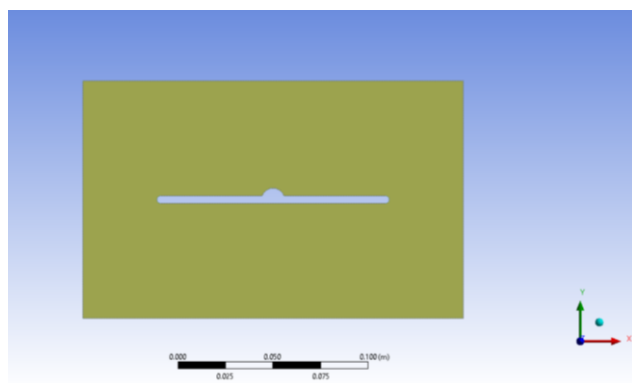


Fig. 5 Throttle (body concept) B

After generating the 2D geometry of the fluid domain, a mesh was generated for both types of the throttle body, which is shown in Figures 6 to 11. The first throttle body concept is labeled A and the numbers on the label indicate the position over the opening percentage, so we have A(100%), A(75%), and A(50%), where the percentages represent the position of 100%, 75%, 50% opening of the throttle body. It should be noted that 100% is a fully open throttle body and 0% is a fully closed throttle body. The same applies to concept B, so numerous values indicate the percentage of throttle body openness.

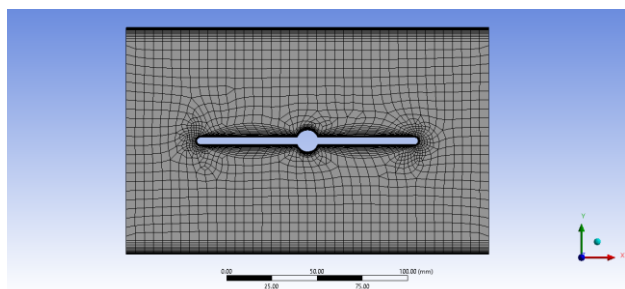


Fig. 6 Mesh for Throttle body A(100%)

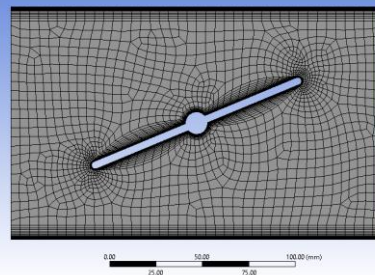


Fig. 7 Mesh for Throttle body A(75%)

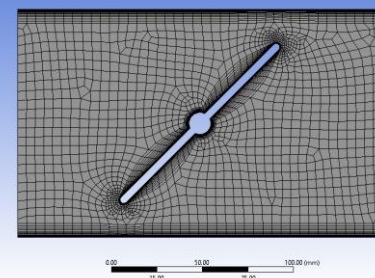


Fig. 8 Mesh for Throttle body A(50%)

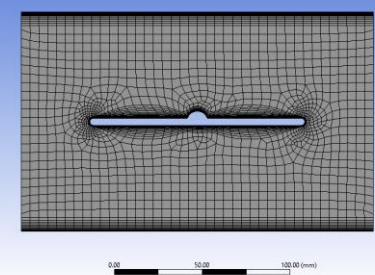


Fig. 9 Mesh for Throttle body B(100%)

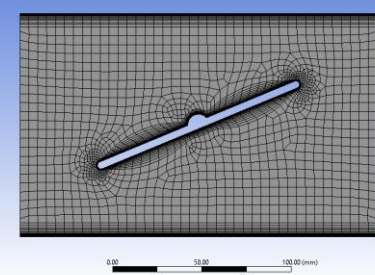


Fig. 10 Mesh for Throttle body B(75%)

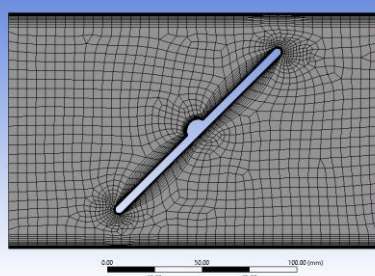


Fig. 11 Mesh for Throttle body B(50%)

Setting up the CFD simulation is what follows after generating the mesh. The standard k-epsilon turbulence model was used in the CFD simulation. After setting up the network, it is necessary to set

the boundary conditions. Air was used as the fluid, and the pressure drop at the outlet compared to the inlet was simulated by 0.1 bar. A pressure of 1 bar was set at the inlet and 0.9 bar at the outlet. For each throttle body out of the three possible cases, it is necessary to define the inlet and outlet of the working fluid, and this is shown only in the example of a 100% throttle body for concepts A and B, in Figures 12 and 13 with the network (inlet - blue arrows, outlet red arrows).

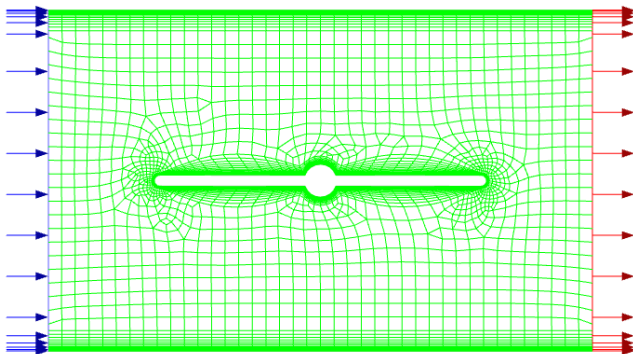


Fig. 12 Inlet and outlet for 100% open Throttle body A

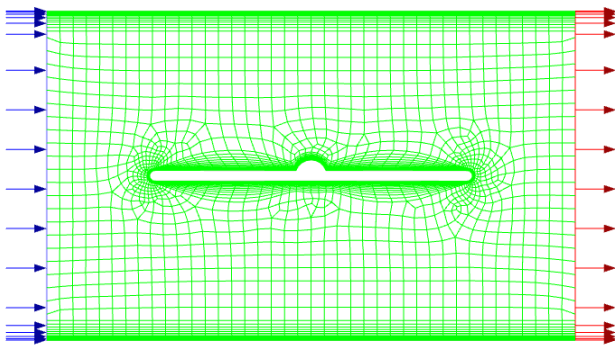


Fig. 13 Inlet and outlet for 100% open Throttle body B

4. Results

The results of CFD simulations of airflow through both throttle bodies A and B for three different opening positions are given in this chapter. Figures 14 to 19 show the contour of pressure for Throttle Body A and B for three positions.

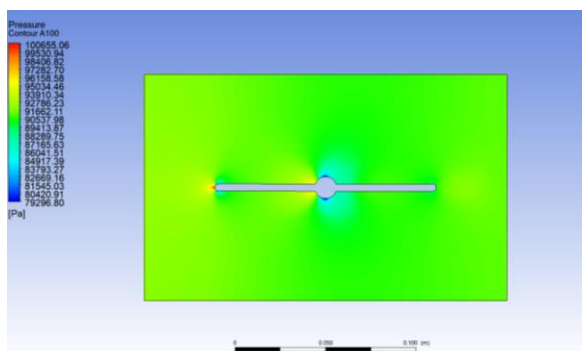


Fig. 14 Pressure contour for Throttle body A(100%)

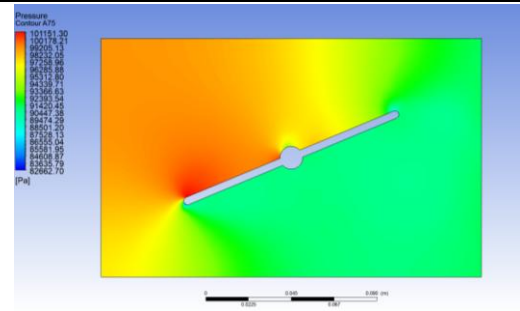


Fig. 15 Pressure contour for Throttle body A(75%)

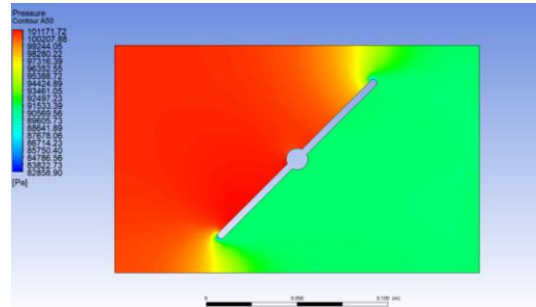


Fig. 16 Pressure contour for Throttle body A(50%)

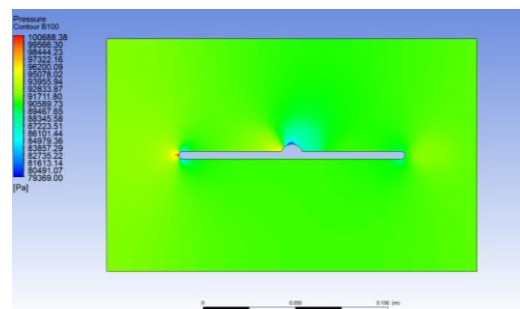


Fig. 17 Pressure contour for Throttle body B(100%)

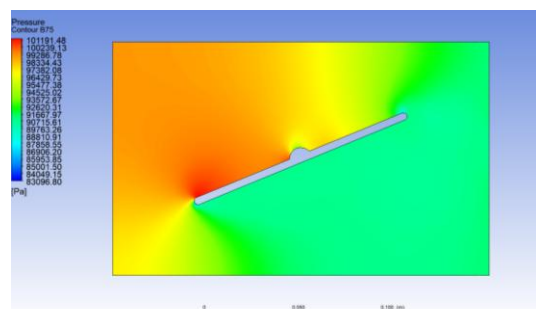


Fig. 18 Pressure contour for Throttle body B(75%)

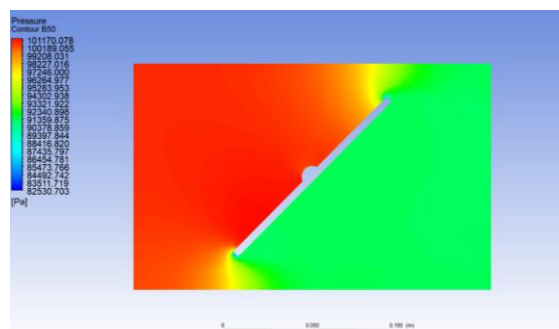


Fig. 19 Pressure contour for Throttle body A(50%)

Velocity contours for both throttle bodies and all three considered opening positions are also shown in this chapter. Figures 20 to 25 show velocity contours for the throttle body and opening positions.

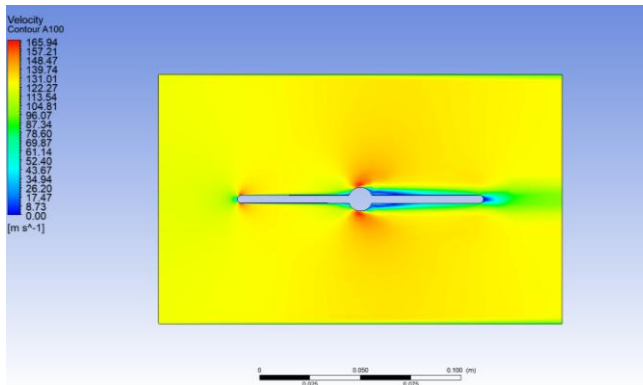


Fig. 20 Velocity contour for Throttle body A(100%)

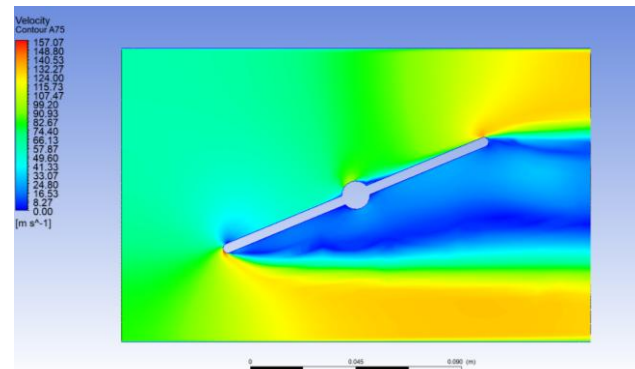


Fig. 21 Velocity contour for Throttle body A(75%)

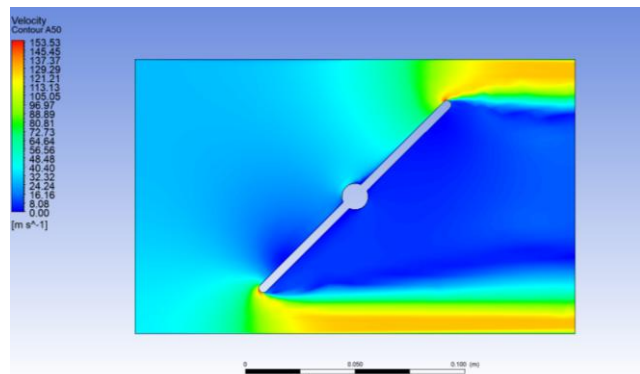


Fig. 22 Velocity contour for Throttle body A(50%)

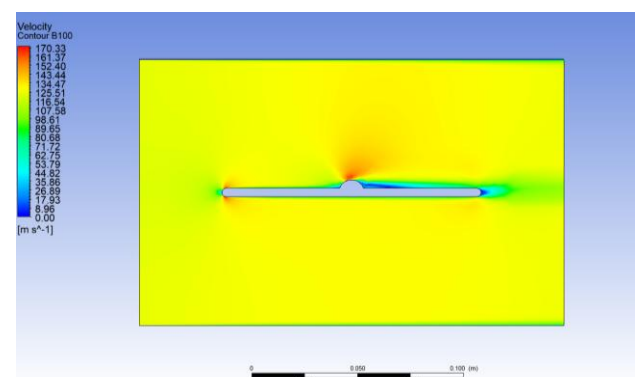


Fig. 23 Velocity contour for Throttle body B(100%)

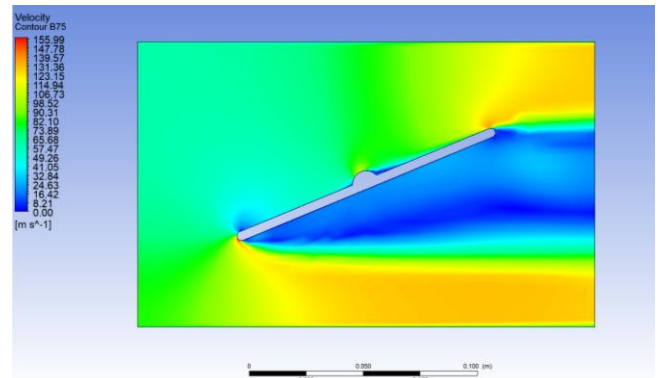


Fig. 24 Velocity contour for Throttle body B(75%)

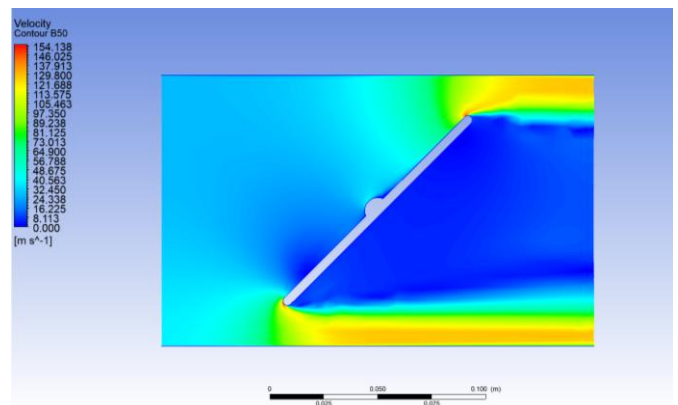


Fig. 25 Velocity contour for Throttle body B(50%)

For an easier overview of the results related to max velocity, a diagram is given in Figure 26.

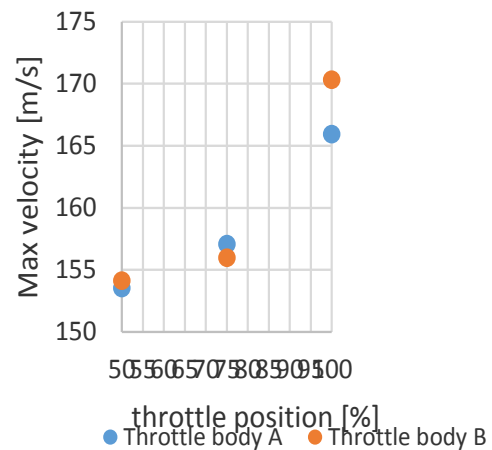


Fig. 26 Maximum velocity in the throttle body

From the previous analysis, it can be concluded that these two throttle bodies are very similar geometrically, and practically similar in results as well. Throttle body B has a higher maximum speed value at full opening (100%), which is logical because it has a smaller surface that creates an obstacle to airflow. A slightly higher maximum speed is achieved by throttle body B even at 50% opening, while at 75% opening the maximum speed is higher with throttle body A.

5. Conclusion

CFD simulation is a standard part of serious engineering practical analysis not only in the automotive industry but also in all other industries dealing with fluids. In the paper itself, it was shown that even if the design of the throttle body is slightly different, the results can differ to a great extent. In this case, it is shown in the example of velocity and pressure at the full opening of throttle body A and B. Investigating the fluid flow in the throttle body can be a very complex job, especially if the considered problem is examined in detail. It has been shown that very simple CFD simulations can simulate the real situation in the example of the throttle body. In the end, it should be emphasized that the biggest influence on the flow is the throttle body's diameter. Special attention should be paid to the correct dimensioning of the throttle body, but also to the shape itself, as well as to the choice of material from which it will be produced. As Formula Student teams are limited by budget, the vast majority decide to make their throttle body design, so CFD simulation can be of great help in choosing a better design.

6. References

1. Ranganathan, S., Thiyagarajan, A. S., Kuppuraj, S., & Chandrasakaran, P. (2019). *Design and Analysis of De-Laval Restrictor with Throttle Body for Formula Vehicle* (No. 2019-28-0009).
2. Lindley, D. (2012). *Design and Optimization of a Throttle and Restrictor for Formula SAE* (Doctoral dissertation, University of Cincinnati).
3. Sharma, V., Dhauni, S., & Chawla, V. K. (2021). Design and manufacturing of air intake assembly for formula SAE vehicle. *Materials Today: Proceedings*, 43, 58-64.
4. Waghmare, S. N., Karekar, N. S., Karande, P. P., & Pandhare, S. B. (2016). Design & Analysis for Intake System of Formula SAE Car. *International journal of Engineering technology, Management and applied sciences*, 4(2), 2349-4476.
5. Jose, J., Shetty, N., Dhumal, A., Anthony, H., & Kushwaha, A. (2018). CFD Analysis of Air Intake Manifold System to Improve Efficiency of Formula SAE Car.
6. Mohamad, B., Karoly, J., & Zelentsov, A. (2020). CFD modelling of formula student car intake system. *Facta Universitatis. Series: Mechanical Engineering*, 18(1), 153-163.
7. Bhope, A., Huwale, S., Aher, V., Dahiwal, R., & Patil, M. N. (2020). DESIGN AND ANALYSIS OF INTAKE SYSTEM FOR FSAE VEHICLE.
8. Xu, C., & Cho, H. (2017). The Analysis of Influence of Throttle Body on Engine Intake System. *International Journal of Engineering and Technology (IJET)*.
9. Lučić, M. (2022). Kinematic analysis of the slider-crank mechanism of an internal combustion (IC) engine using modern software. *Mechanization in agriculture & Conserving of the resources*, 68(1), 11-17.
10. Mike, Narvigia. (2014). *Performance Exhaust Systems: How to Design, Fabricate, and Install*. CarTech, ISBN 978-1-61325-207-9
11. Harty, R. T. (2017). *The Design and Testing of a High Performance Formula SAE Powertrain*.
12. Formula Student Rules. (2022). SAE

The prospects for the use of liquefied gas in maritime transport

Romanov Topuria¹, Mikheil Lezhava², Zaza Shubladze², Jemal Sharadze², Akaki Katsadze²

Akaki Tsereteli State University, 59 Tamar Mepe str, Kutaisi 6400, Georgia¹
 Batumi State Maritime Academy, Rustaveli Av. 53, Batumi 6010, Georgia²
 Romtop54@gmail.com, m.lejava@bsma.edu.ge, z.shubladze@bsma.edu.ge,
 j.sharadze@bsma.edu.ge, mr.katsadze@yahoo.com,

Abstract. *If a fuel mixture consisting of a liquefied gas fuel is prepared in the water transport diesel engines, i.e. the gas-diesel process occurs, where methanol is used as an explosive fuel, resulting in the reduction of the self-ignition delay period and fuel combustion duration, the limits of the working mixture combustion are expanded (hybrid combustion), and the mixture formation process is improved, resulting in an increase in the combustion speed, i.e., the complete combustion of the fuel mixture occurs during the active combustion period, and the cycle in the engine is closer to the Otto cycle, which improves the environmental and efficient indicators of diesel engine compared to the gas-diesel engine, where the diesel fuel is used as an explosive fuel.*

Key words: gaseous fuel; liquefied gas; diesel engine; methanol; explosive fuel, dosing.

1. Introduction

One hundred years ago, transportation switched from a coal fuel to the petroleum pitch. Another hundred years later, the transition to a new fuel source is increasing, but this time - to gas.

According to stricter international and environmental standards, LNG (liquefied natural gas) is considered to a fuel of the future. According to experts, in the near future it is expected that LNG will be the main fuel in large-scale transportation. According to DNV, LNG may be the best option for many ships. The high prices of diesel fuel have led to the development of new technologies for the cost-efficient and environmentally friendly fuels such as liquefied natural gas. LPG is a potential winner in terms of environmental friendliness, safety, reliability and efficiency. Compared to oil, liquefied natural gas has become an important fuel with a significant impact on a global energy. Thanks to its powerful properties, liquefied natural gas is considered the only alternative fuel with a future. Studies have shown that use of liquefied natural gas (LNG) as a fuel has significantly reduced emissions of toxic sulfur or SO_x, as well as the emissions of carbon dioxide (CO₂) and nitrogen oxides or NO_x. The LNG-powered engines can emit almost zero sulfur oxide, which is relevant when the 2015 ECA or ECA regulations come into force. Due to the low carbon content in LNG, harmful carbon dioxide emissions are reduced by almost 25 percent. As is known, the piston internal combustion engines in the modern period are the most economical of all other heat engines, which leads to their wide use in all fields. An important disadvantage of the piston internal combustion engines is that most of them run on liquid fuels of petroleum origin. Prospects for their further development and use directly depend on the complex changes in gaseous fuels (the use of alternative fuels).

2. Preconditions and means for resolving the problem

When ships run on engine powered by non-traditional diesel fuel, a number of difficulties arise related to fuel supply to cylinders, improving the mixture formation process, ensuring the ignition process in the combustion chamber, and the peculiarities of the combustion processes in accordance with the required characteristics. It should also be taken into account the ratio governing of the load carried out in the diesel engine, where the air excess ratio α depending on the load varies over a wide range $\alpha = 5$ and over, at low engine power and in idling conditions, and $\alpha = 1.35 - 1.25$ at full engine load. The range of admissible change of α depends significantly on the properties of the fuel used. Therefore, converting a diesel engine to run on a gaseous fuel provides a reduction in toxicity and smokiness in exhaust gases, as well as

lowers fuel costs. It should be noted that the transport diesel engines run, typically, on compressed natural, as well as liquid natural fuel. When using liquefied gas, fuel costs increase significantly compared to compressed natural gas. Instead, when using the latter, it is possible to fully compensate for the loss of power. So, great importance is attached to the use of liquefied natural gas in the internal combustion engines of water transport. Hydrogen, also belonging to the series of liquid fuels, is the most environmentally friendly fuel in nature with an unlimited supply. It is present in 90% of the components existing in the environment and in more than a third of the components on the earth's surface. One of the disadvantages of using hydrogen as a fuel for an internal combustion engine is the high energy required for its compression and the very low specific energy intensity. There are also problems with its storage, especially in the cryogenic tanks, but the main problem is the high cost of its extraction. It is more promising to use hydrogen in a vehicle as fuel cells, especially using proton exchange membranes. The first cars with fuel cells have already been demonstrated by the companies such as: Toyota, Honda, Volkswagen, BMW, Nissan, Hyundai, but the establishment of their industrial production takes time.

The automotive diesel engines are converted by a gas diesel cycle, as well as with spark ignition working on a natural fuel. It is technically easy to work with the converted gas-diesel cycle, in addition, it retains the possibility to run on a standard diesel fuel, that is, only on a diesel fuel. In the gas-diesel cycle engines, the ratio governing of load is also used, which ensures that the formation of a highly enriched mixture is avoided, which is associated with a significant increase of $C_n H_m$ in the exhaust, and therefore the formation of a rich mixture leads to the reduction of fuel efficiency [1].

One of the most promising operation processes of the transport diesel engine is a gas-diesel cycle operation. The gas-diesel process has potential advantages over the forced-ignition process. It is known that the highest efficiency of the diesel engine is $\eta_e = 0.42 - 0.44$. In the implementation of the gas-diesel cycle, both external and internal mixings are used. Due to simple design, the external mixing has gained widespread use in transport engines. In this case, the mixer is made in the form of a nozzle installed in the air path. Liquefied gas is supplied to the mixer at a pressure close to atmospheric, in order to exclude gas leakage into the environment and prevent air from entering the gas tube. The good properties of liquefied natural gas fuel for mixing result in the possibility of wide application of internal mixing. Especially the main difficulty is the high self-ignition temperature of natural gas (650-700 °C), which significantly exceeds the self-ignition temperature of a liquid diesel fuel (320-380 °C). In terms of the closest approach to this process, we can consider injection of liquid gas fuel individually into the cylinder at the beginning of filling in front of the inlet valve (external mixing), and at the end of the compression process, igniting it with a small dose of diesel fuel or methanol, the amount

of which does not exceed 15-20%, which enables us to use the serial diesel engine without changing the compression ratio [2].

When using the gas-diesel cycle, the engine performance is improved by 10-15% compared to standard diesel engine. In order to maintain the power indicator, during the implementation of the gas-diesel process, it is necessary to provide governing ratio of the working mixture in such a way that, accordingly, at any load mode of the engine, such a value of α is selected that ensures power compensation. This would be achieved based on the conditions that we assume that the heat released by combustion at each load mode of a standard engine would be equal to the amount of heat released by combustion of a gas-diesel cycle engine at the same modes. Therefore, the following equality will hold: $Q_{di}=Q_{gi}$ or $H_{di}=H_{gi}$. For a standard diesel engine ($\alpha > 1$), the heat of the working mixture combustion is

$$H_{di} = \frac{H_{ud}}{1 + \alpha_{di} l_{do}}$$

while for a gasi-diesel engine ($\alpha > 1$)

$$H_{gi} = \frac{H_{ug}}{1 + \alpha_{gi} l_{go}} + \frac{H_{ud}}{1 + \alpha_{di}^2 l_{do}}$$

where

- H_{di} and H_{gi} are the amounts of heat released by the complete combustion of the working mixture of a standard diesel and gas-diesel engines loads, respectively.
- H_{ud} and H_{ug} are the lowest heating capacity of diesel and gas fuels, respectively.
- α_{di} and α_{gi} - values of the air excess ratio according to diesel and gas diesel engines loads.
- l_{do} and l_{go} , respectively, the amounts of air theoretically required for the complete combustion for diesel and gaseous fuel.
- α_{gi} and α'_{di} - values of the air excess ratio caused by the amount of gaseous and explosive fuels in a gas diesel engine.

The influence of the explosive fuel dosage and injection timing angle on a gas-diesel engine performance is also important. .

3. Conclusion

In order to assess the influence of the explosive fuel dosage, we introduce the notion of dynamic factor, which shows how much explosive fuel is required in the working mixture for each mode, and it is expressed as follows

$$K = G_{di}/G_{gi}$$

where G_{di} - the amount of explosive fuel, G_{gi} - the amount of gaseous fuel.

The analysis of the main indicators of the above alternative fuels and the characteristics of the operation of water transport engines shows what a decisive factor is the use of liquefied gases, which determines the prospects for the use of fuel in the piston internal combustion engines for marine purposes, instead of liquid petroleumderived fuels.

4. References

1. Pfoser S., Aschauer G., Simmer L., Schauer O. Facilitating the implementation of LNG as an alternative fuel technology in landlocked Europe. A study from Austria. Research in transportation Business and management. 2016. Vol.18, p.77-84
2. В. Л. Жданов, Е. А. Григорьева, А. Н. Карасев; Экологические проблемы автомобильного транспорта, Кемерово : Кузбассвуиздат, 2014, p 202

Improving wellbore stability by applying drilling mud with Fe₂O₃ nanoparticles

Petar Mijić, Igor Medved, Bojan Kuhar, Petra Matešković, Marcela Vargić, Domagoj Mrnjavčić, Karlo Findri
University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, 10 000 Zagreb, Croatia
petar.mijic@rgn.hr

Abstract: Since 90% of all problems related to the wellbore instability occur during drilling through shales, which are mostly consisted of clay minerals, the filtrate from drilling mud penetrate into shale rocks and lead to their destabilization, so the industry is considering the possible application of new types of additives because conventional additives, due to their size, cannot enter in pores of shales, plug them and reduce further filtrate penetration. The oil industry in last few years turns to investigate possible application of nanoparticles because they can enter in small shale pores and plug them, thus increasing the wellbore stability. In this paper the influence of the size (50 nm and between 20 and 30 nm) and concentration (0.5, 1, 3 and 5 wt%) of Fe₂O₃ nanoparticles on density, rheology, API filtration, and swelling of laboratory prepared pellets in contact with mud without and with nanoparticles was determined. Due to the fact that the rheological properties are significantly increased at higher concentrations, and that smaller particles give better results with an emphasis on increasing the wellbore stability further tests should be carried out with nanoparticles Fe₂O₃ which size is between 20 and 30 nm in maximum concentration of 1 wt%.

Keywords: Fe₂O₃ NANOPARTICLES, DRILLING MUD, RHEOLOGY, API FILTRATION, PELLET SWELLING

1. Introduction

Water-based mud has been used to flush wellbore since the early 1900s. From then until the present day, the industry has been working on the development of new additives that must meet the increasing technical, economic, and environmental requirements that are imposed during the wellbore drilling [1]. Changes are also taking place in the field of drilling fluids - muds, because the classic additives used in muds, which have relatively larger dimensions, are not always suitable for solving problems that arise during the wellbore drilling through different rocks. Analyzing the data from the literature, 90% of all problems related to the wellbore instability occur during drilling through shales, rocks that make up 75% of all rocks through which the wellbore is drilled [2]. Wellbore instability is defined as any unwanted change in the wellbore diameter (narrowing or expansion) in relation to the diameter of the drill bit used to make the individual section of the wellbore, and it represents one of the leading problems during drilling. During drilling, water from drilling mud penetrate into shale and lead to its destabilization because conventional additives cannot enter in shale pores, due to their size, plug them, reduce further penetration of the water and increase wellbore stability. Therefore, for the past ten years nanoparticles are considered as potential additive because its diameters range from 1 to 100 nanometers so they can enter in shale pores, plug them and increase the wellbore stability [3]. These mud additives are added to mud in order to adjust its properties, and they can be in liquid or solid state (powder material). Nanoparticles have begun to be tested in the laboratory, and examples of their successful application in the field can already be found, especially for solving problems related to the construction of well channels [4]. In this paper, the impact of adding Fe₂O₃ nanoparticles, as one of the most common types that has been tested in laboratory conditions so far, was examined because of their greatest distribution and ease of delivery. Table 1 shows an overview of previous tests on the impact of Fe₂O₃ nanoparticles on different mud properties, with an emphasis on mud properties related to wellbore stability (filtration) and the possibility of using such muds in practice (rheology). The size of Fe₂O₃ nanoparticles in all tests was less than 50 nm, and they were added in different concentrations (up to 2.5 wt% at most).

Within the framework of this paper, laboratory tests were carried out on the influence of the size and concentration of Fe₂O₃ nanoparticles (sizes 50 nm and between 20 and 30 nm) on the following mud properties: 1) density, 2) rheology, 3) API filtration, and 4) swelling of laboratory prepared pellets in contact with mud without and with nanoparticles. The tests were carried out by adding nanoparticles to a simple bentonite suspension, in 4 concentrations: 0.5, 1, 3 and 5 wt%. In a laboratory test, the influence of the size and concentration of Fe₂O₃ nanoparticles on the properties of a bentonite suspension was determined, based on the sizes and concentrations of nanoparticles that are able to increase the wellbore stability and which are considered to be able

to be further tested with the aim of application in muds of more complex composition.

Table 1: The influence of the Fe₂O₃ nanoparticles used in various laboratory studies on the filtration and rheological properties of drilling muds

Literature	Vryzas et al., 2015 [5]	Mahmoud et al., 2016 [6]	Mahmoud et al., 2018 [7]
Concentration (%wt)	0.5, 1.5 and 2.5	0.3, 0.5, 1.5 and 2.5	0.3, 0.5 and 1
Drilling mud formulation	Deionized water to which bentonite has been added in a concentration of 7 wt%		Deionized water to which bentonite has been added in a concentration of 7 wt%, PAC, Fe-Cr-lignosulfonat, NaOH, CaCO ₃ , Mn ₃ O ₄
Type of filtration test and conditions	API filtration; HTHP filtration (Δp= 20.7 bar [300 psi], T=121 °C [250 °F])	HTHP filtration (Δp=13.8-34.5 bar [200-500 psi], T=79.4 °C -176.7 °C [175-350 °F])	HTHP filtration (Δp=20.7 bar [300 psi], T=121 °C [250 °F])
Rheology equipment and conditions	Grace M3600 viscometer	49 to 93 °C	60 °C
The influence of adding nanoparticles on filtration	Decrease	Decrease	Decrease/increase depending on the concentration
The influence of adding nanoparticles on rheology	Increase plastic viscosity and yield point values	Increase plastic viscosity and yield point values	Decrease plastic viscosity and slightly increase yield point values

2. Laboratory testing

Laboratory testing was performed at the Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Croatia. Fe₂O₃ nanoparticles used were in the form of an aqueous suspension. In this research two types of Fe₂O₃ nanoparticles were used, nanoparticles which average particle size was 50 nm and

between 20 and 30 nm. Nanoparticles used in this research were in the form of an aqueous suspension. Typical data for Fe₂O₃ nanoparticles used in laboratory research are shown in table 2.

Table 2: Typical data for nanoparticles used in laboratory research

Brand name	SAT-02	SAT-01
Manufacturer	SAT nano Technology Material CO., Ltd.	
Appearance	an aqueous suspension	
Nanoparticles content in aqueous suspension	20 wt%	25 wt%
Average particle size (D50)	50 nm	between 20 and 30 nm

As base drilling mud was chosen bentonite-based drilling mud (BM) which was prepared by adding 70 g of bentonite to 1 liter of water. Muds with nanoparticles were prepared in such a way that 70 g of bentonite and 5, 10, 30 and 50 g of Fe₂O₃ nanoparticles were added to 1 liter of water (water from aqueous suspension + added water). All muds were prepared according to American Petroleum Institute Standards, API Specifications 13A (1993) and API 13B-1 (1997) [8]. Drilling mud formulation used in this laboratory research is shown in table 3.

Table 3: Drilling mud formulations

Mud formulation	Nanoparticles concentration added to drilling mud (wt%)				
	0	0.5	1	3	5
Water (ml)*	1 000	1 000	1 000	1 000	1 000
Bentonite (g)	70	70	70	70	70
Nanoparticles (g)	0	5	10	30	50
* water from aqueous suspension + added water					

Within the framework of this paper, laboratory tests were carried out on the influence of the size and concentration of Fe₂O₃ nanoparticles (sizes 50 nm and between 20 and 30 nm) on the density, rheology, API filtration and swelling of laboratory prepared pellets. The equipment and measurement procedures are shown in table 4.

Table 4: Laboratory test equipment and measurement procedures

Test	Equipment	Measurement procedures and conditions
Density	Mud balance	The balance cup was filled with the drilling mud to the limit. Balance the assembly by moving the rider along the arm. Read the sample weight from the side of the rider nearest the balance cup.
Rheology	Fann viscometer	Shear stress data were obtained at six fixed shear rates of 5.1, 10.2, 170, 340, 510 and 1020 s ⁻¹ . According to equations shown in paper Mijić et al. (2021) [9] plastic viscosity (PV) and

		yield point (YP) values were calculated for all tested muds.
API filtration	API filter press	API filtration was carried out at a pressure of 7 bar (100 psi) and room temperature. Filter media was Whatman filter paper No. 50 and filtration area was 45.8 cm ² . Test was carried out for 30 minutes, while filtrate volume was recorded after 30 minutes.
Pellet swelling	Compactor and linear swellmeter	A mixture of 6 g of bentonite and 6 g of quartz was placed in a compactor, which was then exposed to the pressure of 41.36 MPa (6000 psi) that remained constant for the 30 minutes. After the compression time has elapsed, the swelling of prepared pellet was measured in linear swell meter.

3. Results and discussion

a) Effect of concentration and size of Fe₂O₃ nanoparticles on mud density

Table 5 shows the measured density values of drilling muds without and with Fe₂O₃ nanoparticles, both sizes.

Table 5: Drilling mud density without and with nanoparticles Fe₂O₃-50 nm and Fe₂O₃-between 20 and 30 nm

Fe ₂ O ₃ nanoparticles (both tested sizes) concentration added to drilling mud (wt%)	Drilling mud density (kg/m ³)
0	1 030
0.5	1 040
1	1 050
3	1 060
5	1 080

By increasing the concentration of Fe₂O₃ nanoparticles in the drilling mud, the density of the drilling mud increases from 1 030 kg/m³, which corresponds to the density of the drilling mud without nanoparticles up to 1 080 kg/m³, as measured at a concentration of Fe₂O₃ nanoparticles (both sizes) of 5 wt%.

b) Effect of concentration and size of Fe₂O₃ nanoparticles on mud rheology

Figure 1 shows the results of the calculated values of the rheological parameters: plastic viscosity (PV) and yield point (YP).

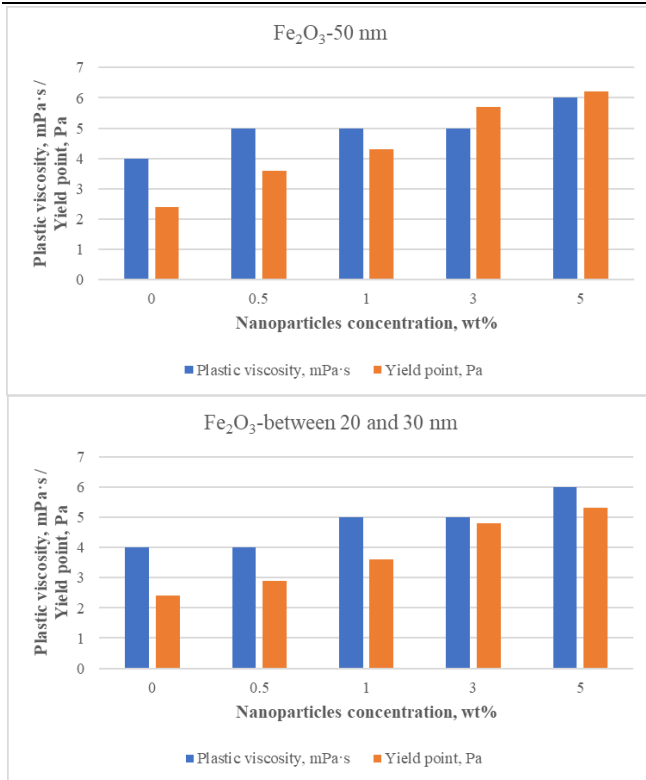


Fig 1. PV and YP of all tested drilling muds

The plastic viscosity (PV) values increase with an increase in the concentration of Fe₂O₃-50 nm nanoparticles above 0.5 wt%, while for Fe₂O₃-between 20 and 30 nm nanoparticles it increases above 1 wt%. The values of the yield point (YP) increase with an increase in the concentration of Fe₂O₃ nanoparticles for both tested sizes, but the measured values were higher for muds containing Fe₂O₃-50 nm nanoparticles.

c) Effect of concentration and size of Fe₂O₃ nanoparticles on API filtration

Figure 2 shows measured data for API filtration of drilling muds without and with Fe₂O₃ nanoparticles (both sizes).

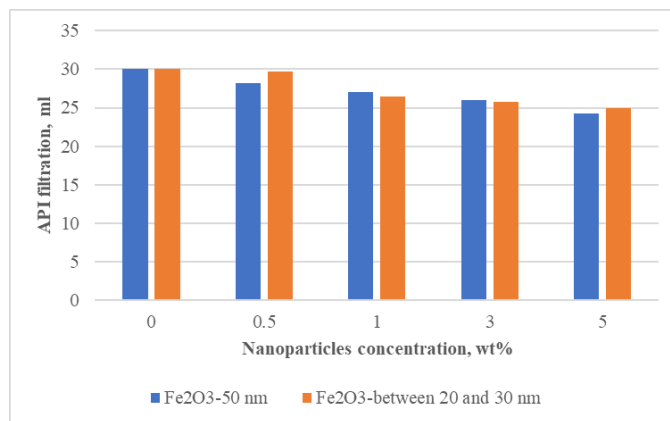


Fig 2. API filtration of drilling muds without and with Fe₂O₃ nanoparticles (both sizes)

In Figure 2 can be seen that by increasing the concentration of nanoparticles the API filtration value decreases for both tested sizes. Comparing both tested sizes, it can be seen that for a certain concentration the API filtration values are slightly different. Table 6 shows the decrease/increase (%) of API filtration of drilling mud with Fe₂O₃ nanoparticles compared to API filtration of drilling mud without nanoparticles (30 ml). Those sizes and concentrations of Fe₂O₃ nanoparticles which reduce API filtration are highlighted in green. Based on the data presented in Table 6, the positive impact of adding Fe₂O₃ nanoparticles to the drilling mud on the reduction of API filtration can be observed at small concentration of 0.5 wt%,

but a more significant decrease in API filtration value was recorded at a concentration of 1 wt% for both tested muds (over 10 %). The best results were achieved by adding 5 wt% Fe₂O₃ nanoparticles which size was 50 nm (reduction of API filtration by 16.67 %) and between 20 and 30 nm (reduction of API filtration by 19.17 %).

Table 6: Decrease/increase (%) of API filtration of drilling mud with Fe₂O₃ nanoparticles compared to API filtration of drilling mud without nanoparticles

Decrease/increase (%) of API filtration		
Fe ₂ O ₃ nanoparticles concentration in drilling mud (wt%)	Nanoparticles size	
	50 nm	between 20 and 30 nm
0.5	-0.83	-5.83
1	-11.67	-10.00
3	-14.17	-13.33
5	-16.67	-19.17

Figure 3 shows the swelling of pellets in mud without and with Fe₂O₃ nanoparticles, both tested sizes. The swelling is expressed in percentages after the pellet has been in contact with the mud for 24 hours.

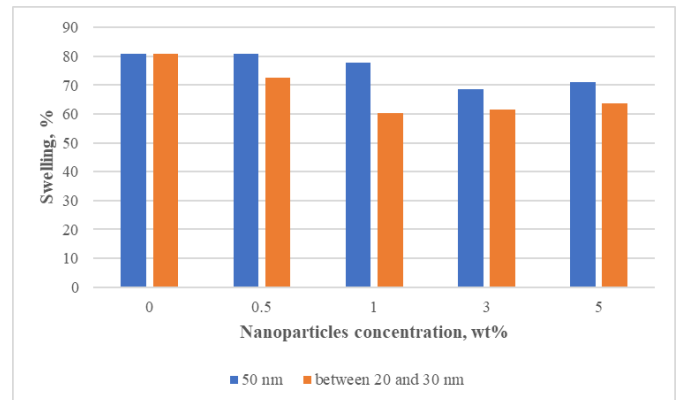


Fig 3. Swelling of pellets in mud without and with Fe₂O₃ nanoparticles expressed in percentages after the pellet has been in contact with the mud for 24 hours

It is evident from Figure 3 that muds with added Fe₂O₃-50 nm nanoparticles in concentrations of up to 1 wt% have no significant influence on the swelling of the prepared pellets and the measured values are similar to the one measured in the drilling mud without nanoparticles (80.9%). By increasing the concentration of nanoparticles up to 3 wt% and more, a significant reduction in swelling is achieved. The addition of Fe₂O₃-between 20 and 30 nm nanoparticles in any concentration reduced the swelling of the prepared pellets, but a more significant decrease was recorded at a concentration of 1wt%. Table 7 shows the decrease/increase (%) of pellet swelling in drilling muds with Fe₂O₃ nanoparticles after 24 hours compared to their swelling in drilling mud without Fe₂O₃ nanoparticles (80.9%). Those sizes and concentrations of Fe₂O₃ nanoparticles which reduce pellet swelling are highlighted in green.

Table 7: Decrease/increase (%) of pellet swelling in drilling muds with Fe₂O₃ nanoparticles after 24 hours compared to their swelling in drilling mud without Fe₂O₃ nanoparticles

Decrease/increase (%) of pellet swelling		
Fe ₂ O ₃ nanoparticles concentration in drilling	Nanoparticles size	
	50 nm	between 20 and 30 nm
0.5	-10.00	-10.00
1	-12.00	-25.00
3	-16.00	-17.50
5	-14.00	-17.50

mud (wt%)		
0.5	0.12	-10.38
1	-3.71	-25.34
3	-15.08	-23.98
5	-11.96	-21.31

Based on the data presented in Table 7, the positive impact of adding Fe_2O_3 nanoparticles on the reduction of pellet swelling in contact with drilling mud can be observed. After 24 hours, the swelling of the pellets in the drilling containing from 0.5 to 5 wt% of nanoparticles Fe_2O_3 -20 to 30 nm was reduced regardless of their size. The best result was obtained by addition of 1 wt% nanoparticles Fe_2O_3 which size was between 20 and 30 nm (25.34%). The addition of Fe_2O_3 -50 nm nanoparticles also reduced the swelling of the prepared pellets, but the results were slightly worse compared to Fe_2O_3 -between 20 and 30 nm.

4. Conclusion

Based on the conducted laboratory tests, the following can be concluded:

- The values of the PV increase slightly with increasing concentration up to 5 wt% for both tested sizes, but YP values were higher for muds containing Fe_2O_3 -50 nm nanoparticles at the same concentration.
- API filtration value decreases by increasing the concentration of Fe_2O_3 nanoparticles for both tested sizes. Also, particle size has a negligible effect on API filtration.
- Analyzing the swelling of the prepared pellets, the positive influence of Fe_2O_3 nanoparticles can be seen. Comparing both types of tested nanoparticles, nanoparticles with a size between 20 and 30 nm performed better, and the swelling of the prepared pellets after 24 hours was significantly reduced at a concentration of 1 wt%. It was significantly less than the swelling measured at any concentration with Fe_2O_3 -50 nm.

Based on the analysis of the application of Fe_2O_3 nanoparticles in a simple drilling mud (bentonite suspension), it can be concluded that positive results are obtained, but due to the fact that the rheological properties are significantly increased at higher concentrations, tests with smaller concentrations (up to 1 wt%) are recommended.

When comparing the results obtained by adding nanoparticles Fe_2O_3 -50 nm and Fe_2O_3 -between 20 and 30 nm, it is evident that smaller particles give better results with an emphasis on increasing the wellbore stability, so further tests should be carried out with nanoparticles Fe_2O_3 which size is between 20 and 30 nm in maximum concentration of 1 wt%.

5. References

- [1] van Oort, E., *On the Physical and Chemical Stability of Shales*, Journal of Petroleum Science and Engineering, 38(3-4), 213–235, (2003)
- [2] Pašić, B., Gaurina Medimurec, N., Matanović, D., *Wellbore instability: causes and consequences*, Rudarsko-geološko-naftni zbornik, 19(1), 87-98, (2007)
- [3] Mijić, P., *Improving wellbore stability using nanoparticle-based drilling fluids*, doctoral dissertation, Sveučilište u Zagrebu, Rudarsko-geološko-naftni fakultet, (2020)
- [4] Barroso, A.L., Marcelino, C.P., Leal, A.B., Odum, D. M., Lucena, C., Masculo, M., Castro, F., *New Generation Nano Technology Drilling Fluids Application Associated to Geomechanic Best Practices: Field Trial Record in Bahia – Brazil*, OTC-28731-MS, Offshore Technology Conference, Houston, Texas, USA, 30 April – 3 May, 1-12, (2018)
- [5] Vryzas, Z., Mahmoud, O., Nasr-El-Din, H.A., Kelessidis, V.C., *Development and Testing of Novel Drilling Fluids Using Fe_2O_3 and SiO_2 Nanoparticles for Enhanced Drilling Operations*, IPTC-18381-MS, International Petroleum Technology Conference, Doha, Qatar, 1-16, (2015)
- [6] Mahmoud, O., Nasr-El-Din, H.A., Vryzas, Z., Kelessidis, V.C., *Nanoparticle-Based Drilling Fluids for Minimizing Formation Damage in HP/HT Applications*, SPE-178949-MS, SPE International Conference and Exhibition on Formation Damage Control, Lafayette, Louisiana, USA, 1-26, (2016)
- [7] Mahmoud, O., Nasr-El-Din, H.A., Vryzas, Z., Kelessidis, V.C., *Effect of Ferric Oxide Nanoparticles on the Properties of Filter Cake Formed by Calcium Bentonite-Based Drilling Muds*, SPE-184572-PA, SPE International Conference on Oilfield Chemistry, Montgomery, Texas, USA, 3-6 April, 1-14, (2018)
- [8] API, R. 13B-1, *Recommended Practice for Field Testing Water-Based Drilling Fluids*, and ISO 10414-1, American Petroleum Institute, (2003)
- [9] Mijić, P., Medved, I., & Mijić, S., *Decreasing pressure losses by applying drilling mud with nanoparticles*, Machines. Technologies. Materials., 15(8), 319-322, (2021)

Study of the radial shear rolling effect on the gradient microstructure formation in technical titanium and mechanical properties changes

Abdrakhman Naizabekov¹, Irina Volokitina¹, Alexandr Arbuz², Andrey Tolkushkin³, Darkhan Nurakhmetov¹

¹Rudny Industrial Institute, Rudny, Kazakhstan

²Nazarbayev University, Astana, Kazakhstan

³Ural Federal University, Yekaterinburg, Russia
naizabekov57@mail.ru

Abstract: The work is devoted to experimental studies of the influence of radial shear rolling on the microstructure evolution of the VT-1 titanium alloy and its gradient distribution over the cross section, as well as changes in mechanical properties. In the course of the conducted studies, two different types of microstructure were obtained. At the periphery of the bar near the surface, a relatively equiaxed ultrafine-grained structure with a grain size of 300-600 nm was obtained, while in the axial zone of the bar, an oriented striped texture was obtained. The resulting structure difference of the peripheral and central zones indicates the gradient nature of the structure distribution. This type of distribution is confirmed by the results of the microhardness study over the cross section of a bar rolled to a diameter of 15 mm. The ultimate strength after deformation increased by 58%, while the elongation decreased by 15%.

Keywords: RADIAL SHEAR ROLLING, GRADIENT MICROSTRUCTURE, TECHNICAL TITANIUM, MECHANICAL PROPERTIES.

1. Introduction

The achievements of modern medicine in the field of implantation are impossible without the productive joint work of scientists, doctors themselves and technical specialists of various specialties, including materials scientists. It was their joint work that made it possible to achieve a long stay in the human body of various implantation materials and structures made of them: rods and plates for connecting damaged bone structures; dentures; endoprostheses and others. But, despite the existing achievements in this direction, there are still problems and questions in the field of development and application of modern materials for implantation. Therefore, the development of both new biocompatible implantation materials and technology for the formation of enhanced, and sometimes unique, properties already in known biocompatible materials is still an urgent direction. At the same time, special attention should be paid to the development of technology for producing long-length products from biocompatible materials with an increased level of mechanical properties.

One of the main and most commonly used methods for increasing the mechanical properties of both ferrous and non-ferrous metals and alloys for more than a decade is the grinding of the structure of these materials to an ultra-fine-grained, and preferably to a nano-structured state [1]. However, for most materials, the growth of strength properties in ultrafine-grained materials is accompanied by an inevitable decrease in its plastic properties, and as a result, such a material becomes brittle and is subject to destruction during stretching. The solution of this problem prompted scientists to develop a new direction in the field of obtaining new materials – the creation of (functional) gradient materials [2]. One of the main features of such materials is the anisotropy of their properties in a given direction, and this is achieved most often by the formation of appropriate structures. The authors of [3-6] have proved that the production of metallic materials with a gradient structure (the coarse-grained state of the metal in the central part of the workpiece, smoothly growing to an ultra-fine-grained state on the surface) is an effective way to increase the plasticity, not of the metal itself, but of metal products as a whole.

It has long been proved that one of the promising and less expensive methods of obtaining ultrafine-grained materials is severe plastic deformation (SPD) [7-8], which can be implemented in metal in various ways [9-13], including the so-called radial shear rolling [14], which just has prospects for obtaining precisely gradient ultrafine-grained materials. This is due to the fact that in the deformation focus during radial shear rolling, a stress-strain state scheme is implemented, which is very close to the all-round compression scheme with large shear deformations. Radial shear rolling also has its own features:

- nonmonotonicity and turbulence of deformation;

- different plastic flow of metal due to the trajectory-velocity features of the process and, as a consequence, different elaboration of the structure of different zones of the workpiece.

2. Experimental part

Due to the peculiarities of the metal flow during radial shear rolling, intense shear deformations are localized in the annular cross-sectional area characteristic of the three-roll scheme. At the same time, in the outer layer of the deformable workpiece, each small trajectory-oriented element undergoes compression deformation along its radius and in the direction of outflow (along the helical trajectory), and stretching deformation across the helical trajectory [15]. It should also be noted that during radial-shear rolling, a constant gradient of velocities and directions of flow along the radius is observed, which also adds additional shear elements to the overall complex picture of the stress-strain state. During such processing, the elements of the structural structure of the metal subjected to an expanding flow with a two-sided sediment (along the trajectory and along the radius) take the form of isotropic isolated particles of high dispersion [15].

As it is known, titanium has biocompatible properties, therefore, the purpose of this work is to study the effect of radial shear rolling on the possibility of forming a gradient structure in it and an increased level of mechanical properties.

The experiment was carried out on the SVP-08 radial shear rolling mill, which is designed for hot deformation of bars of solid circular cross-section made of various metal (ferrous and non-ferrous metals and alloys) and composite materials. VT-1 titanium rods (0.08% C; up to 0.25% Fe; up to 0.07% C; up to 0.1% Si; up to 0.04% N; up to 0.2% O, 99.24-99.7% Ti) with an initial diameter of 30 mm were used as initial blanks. The choice of this grade of titanium is due to the fact that it has mechanical properties commensurate with the mechanical properties of non-rusting steels, and titanium alloying and heat treatment of alloys based on it can achieve the strength level of high-strength steels. Based on the recommendations of works [16-17], titanium rods were rolled on a radial shear rolling mill at a temperature equal to 500 ° C. At the same time, rolling was carried out to the final diameter of 15 mm in stages, i.e. in 5 passes, with compression of 3 mm in each pass. After the 5th pass, the bars were subjected to intensive cooling with water. The bars were also subjected to intensive cooling with water after each pass, which were intended not for further deformation, but for studying the evolution of the microstructure and changes in mechanical properties.

3. Results and discussion

After rolling and cooling, cylinders with a length of 30 mm were cut out of rods of various diameters (from 27 to 15 mm), as well as the original rod. After that, samples for mechanical tests, microhardness measurements and microstructure studies on a

transmission electron microscope were cut into strips of $0.3 \times 3 \times 30$ mm in size along these cylinders on a high-precision AccuTom-5 cutting machine. Subsequently, samples for microstructure research on a transmission electron microscope JEM-2100 (JEOL, Japan) at an accelerating voltage of 200 kV were subjected to electrolytic thinning on a TenuPol-5 installation to obtain a thin foil from the peripheral and axial zones of the rod along the rolling direction. The most characteristic view of the microstructure of both parts of the rod is shown in Figure 1.

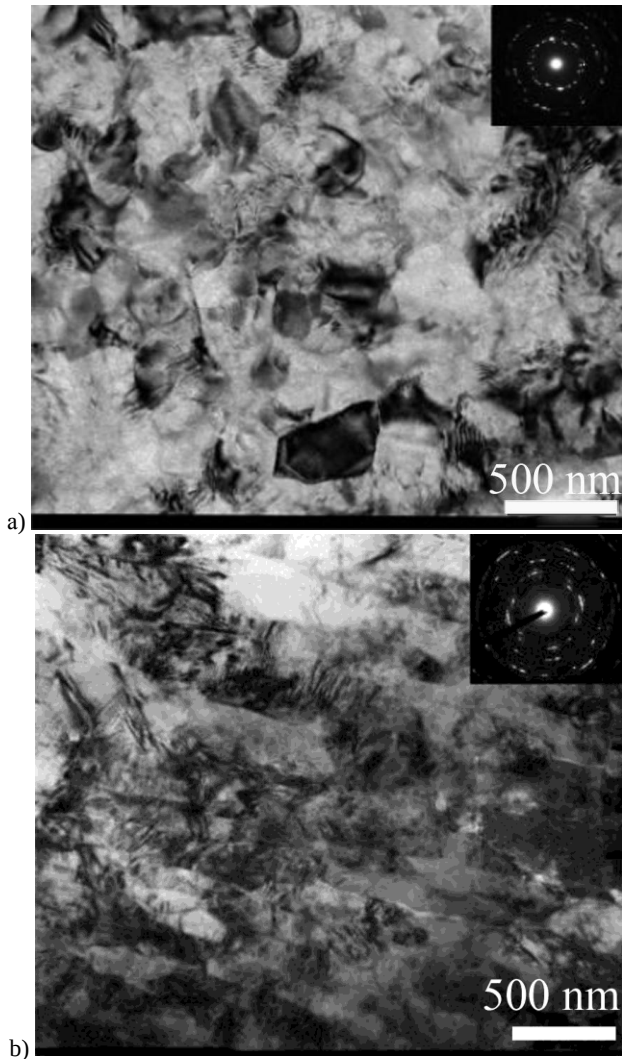


Fig. 1. Titanium structure after radial shear rolling up to a diameter of 15 mm and cooling in water: a - peripheral part of the bar; central part of the bar

Metallographic analysis showed that technical titanium of the VT-1 brand in its initial state has a coarse-grained structure with an average grain size of 70-80 microns. As expected, the microstructure of the peripheral and axial zones after radial shear rolling up to a diameter of 15 mm was not the same. Thus, in the peripheral region of the rod, the microstructure is represented to a greater extent by equiaxed ultrafine grains of 300-600 nm in size, which have high misorientation angles, which is established by the diffraction pattern. The microstructure of the axial zone of the rods after deformation on the radial shear rolling mill is represented by long and narrow grains elongated in the direction of rolling, that is, it is a fibrous texture. The diffraction pattern also confirms the small angles of grain misorientation. That is, as a result, in the peripheral part of the rod, where shear deformation with high turbulence of the metal flow prevailed, we have an equiaxed ultrafine-grained structure, and in the axial zone, where the metal flow had a laminar character along the rolling axis, we have an elongated, oriented structure, resembling the texture of rolling.

Tensile tests carried out on the Instron-1195 testing machine (ITW Inc., USA) showed that the tensile strength after radial shear rolling increased from 704 MPa to 1215 MPa, which is 58%, and the elongation after the fifth pass decreased from the initial 26% to 11%. The values of the tensile strength and relative elongation averaged after each pass (according to the results of 3 experiments with each degree of compression) are shown in Figure 2.

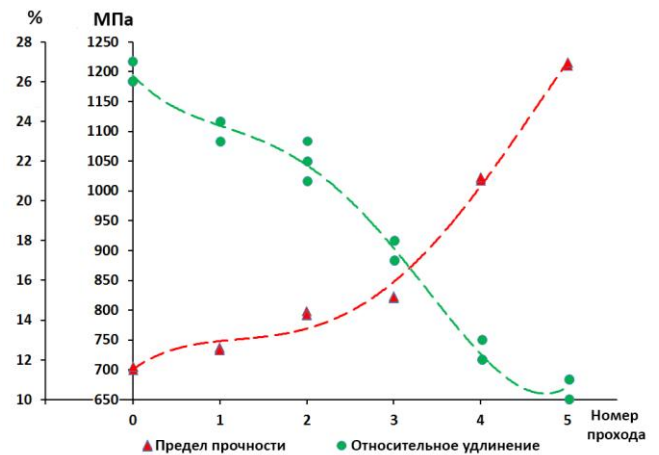


Fig. 2. Change in the tensile strength and elongation of titanium grade VT-1 after radial shear rolling by passes

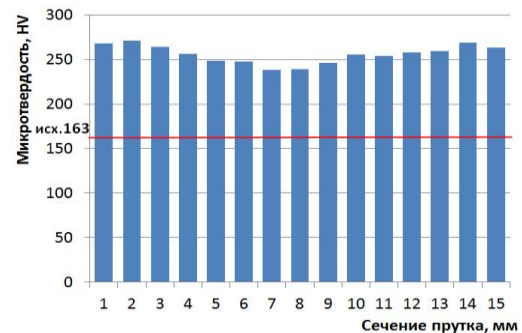


Fig. 3. Change in microhardness of titanium grade VT-1 along the cross section of the bar after radial shear rolling up to a diameter of 15 mm

Taking into account the heterogeneity of the resulting microstructure, microhardness was measured by the cross section of a titanium rod rolled to a diameter of 15 mm on the HVS-1000B microhardness meter (Winex Instrument, UK), which allowed us to construct the microhardness profile shown in Figure 3. Microhardness measurement was carried out by Vickers with a force of 9.87 N at a shutter speed of 15 seconds. The microhardness profile was constructed based on the results of measurements at 15 consecutive points located 1 mm apart.

After radial-shear rolling of a titanium bar to a diameter of 15 mm, the initial microhardness level rose from a value of 163 RM to 238-271 RM, i.e. on average by 60%. At the same time, due to the structural heterogeneity in the cross-section of the bar after rolling, the expected gradual decrease in the microhardness level in the central part by 12.4% relative to the periphery of the part of the bar is observed.

Conclusion

In the course of the conducted research on the deformation of rods made of technical titanium of the VT-1 brand on a radial shear rolling mill, a microstructure of two different types was obtained in them. Thus, a relatively equiaxed ultrafine-grained structure with a grain size of 300-600 nm was obtained at the periphery of the rod, while an oriented, striped texture was obtained in the central zone of the rod. The discrepancy in the structure of the peripheral and central zones of titanium alloy rods formed on the SVP-08 radial shear rolling mill indicates the gradient nature of the structure formed in the resulting rods. This was also confirmed by the results of measur-

ing and constructing a micro-hardness profile along the cross section of a bar rolled up to a diameter of 15 mm. A significant change in the initial microstructure of the titanium rod led to a significant increase in the tensile strength of this rod (by 58% after drawing equal to 4) and a decrease in the plastic characteristic (elongation) with this drawing from 26% to 11%. At the same time, there was a systematic increase in strength characteristics and a decrease in plastic characteristics after each deformation cycle.

This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant no. AP14869128).

References

1. Structural nanocrystalline materials: Fundamentals and applications.// C.C. Koch, I.A. Ovid'ko, S. Seal, S. Veprek// Cambridge, Cambridge University Press, 2007.
2. Лисовский А.Ф. Формирование градиентной структуры в спеченных твердых сплавах (Обзор)// Сверхтвердые материалы, 2010, № 4, pp. 36-53.
3. Raab G.I., Simonova L.A., Aleshin G.N. Tailoring the gradient ultrafine-grained structure in low-carbon steel during drawing with shear // *Metalurgija* 55 (2016) 2, 177–180.
4. Raab A.G., Zhilyaev A.P., Kodirov I.S., Aleshin G.N. Features of structure formation and mechanical behavior of metallic materials under conditions of application of gradient deformations.// *International Journal «Machines, Technologies, Materials»*, 2019, p.105-106.
5. Raab G.I., Raab A.G., Zhilyaev A.P. Gradient structure and methods for their preparation.// *International Journal «Machines, Technologies, Materials»*, 2019, p.132-133.
6. Raab G.I., Kodirov I.S., Aleshin G.N., Raab A.G., Tsenev N.K. Influence of special features of the gradient structure formation during severe plastic deformation of alloys with different types of a crystalline lattice. *Vestnik Magnitogorskogo Gosudarstvennogo Tekhnicheskogo Universiteta im. G.I. Nosova* [Vestnik of Nosov Magnitogorsk State Technical University]. 2019, vol. 17, no. 1, pp. 64–75. <https://doi.org/10.18503/1995-2732-2019-17-1-64-75>
7. Wojtas D., Wierzbowski K., Chulist R., Pachla W., Bieda-Niemiec M., Jarzebska A., Maj L., Kawalko J., Marciszko-Wiackowska M., Wronski M. Microstructure-strength relationship of ultrafine-grained titanium manufactured by unconventional severe plastic deformation process. *Journal of Alloys and Compounds*. 2020. Vol. 837, № 155576.
8. Torabi H., Faraji G., Masoumi A. Processing characterization of binary Mg-Zn alloys fabricated by a new powder consolidation combined severe plastic deformation method. *Journal of Alloys and Compounds*. 2020. Vol. 832. № 154922.
9. Khelfa T., Munoz-Bolanos J.A., Li F., Cabrera-Marrero J.M., Khitouni M. Microstructure and Mechanical Properties of AA6082-T6 by ECAP Under Warm Processing. *Metals and Materials International*. 2020. Vol. 26, Iss. 8, pp. 1247-1261.
10. Shchetinin I.V., Bordyuzhin I.G., Sundeev R.V., Menushenkov V.P., Kamynin A.V., Verbetsky V.N., Savchenko A.G. Structure and magnetic properties of Sm 2 Fe 17 N x alloys after severe plastic deformation by high pressure torsion. *Materials Letters*. 2020. Vol. 274. № 127993.
11. Lin G.Y., Xiao M.Q., Feng D., Liu X.Y., Wang H.Y., Zhang R. Microstructural and mechanical properties of ZA10 alloy tubes and their weld seams prepared by Conform continuous extrusion. *Rare Metals*. 2020. Vol. 39, Iss. 6, pp. 707-715.
12. De Rango P., Fruchart D., Aptukov V., Skryabina N. Fast Forging: A new SPD method to synthesize Mg-based alloys for hydrogen storage. *International Journal of Hydrogen Energy*. 2020. Vol. 45, Iss. 14, pp. 7912-7916.
13. Konstantinov D.V., Korchunov A.G., Zaitseva M.V., Shiryayev O.P., Emaleeva D.G. Macro- and Micromechanics of Pearlitic-Steel Deformation in Multistage Wire Production. *Steel in Translation*. 2018. Vol. 48, Iss. 7, pp. 458-462.
14. Патент РФ № 2293619. Способ винтовой прокатки / С.П. Галкин. 20.02.2007. Бюл. 5.
15. Galkin S.P. Radial shear rolling as an optimal technology for lean production // *Steel in Translation*. – 2014. №44 (1). – P. 61-64.
16. C.S. Meredith, A.S. Khan. Texture evolution and anisotropy in the thermo-mechanical response of UFG Ti processed via equal channel angular pressing. *International Journal of Plasticity* 30–31 (2012) 202–217.
17. G.I. Raab , R.Z. Valiev , D. V. Gunderov , T. C. Lowe, A. Misra, Y.T. Zhu. Long-length Ultrafine-grained Titanium Rods produced by ECAP-Conform. *Materials Science Forum Vols. 584-586* (2008) pp 80-85.

Welding technology of martensitic steel P91 and austenitic steel 304H – State of the art

Aleksandra Krstevska¹, Dobro Runchev¹, Filip Zdraveski¹

University „Ss. Cyril and Methodius“, Faculty of Mechanical Engineering, Rugjer Boshkovikj 18, P.O. Box 464, MK-1000
Skopje, Republic of N. Macedonia¹
aleksandra.krstevska@mf.edu.mk

Abstract: Many industries nowadays with the development of technology require joints between different types of steel due to its various benefits such as production of lightweight machine parts, production of less expensive components with acceptable properties, high strength, acceptable corrosion resistance. One of the dissimilar welding challenges is the joint between martensitic steel P91 and austenitic steel 304H due to the dissimilarities in their chemical, physical and metallurgical properties. In this paper is going to be analysed the best way of joining the two different types of steel, the proper welding technique, the choice of filler material which according to carbon content can match only to one of the steels. At the end is discussed if the welding performance can meet the requirements of high-quality weld.

Keywords: P91, 304H, DISSIMILAR METAL WELD, WELDING TECHNOLOGY

1. Introduction

The coal-fired power plant systems today are striving to work in supercritical steam parameters and assure higher efficiency. The need for higher efficiency is met with higher steam parameters, increase of steam pressure and steam temperature. Another parameter that coal-fired power plants need to incorporate is the method for clean energy, the use of coal needs to satisfy the environmental requirements and take care about the air pollutants [1]. When it is discussed about higher efficiency in power plants and satisfying the environmental requirements for clean energy in coal-fired power plants it means a saving in fuel and less emission of carbon dioxide which reduces the rate at which damage is done to the global environment.

The need for higher efficiency in power plants today relates to the development of new materials with great properties on high temperatures. The possibility for higher steam parameters and working of the plant on super-critical temperatures is met with the development of new enhanced materials.

The new materials resistant to high operating temperatures, also called heat resistant steels, are used for manufacture of ultra-super critical parts of boiler plants such as steam lines, tubes for super heaters, collectors. Regarding construction of power units based on steam with ultra-supercritical parameters the operation of pressure elements in the high range of thermal and mechanical loads require the use of creep resisting construction materials with increased creep strength and advanced welding technologies for joining these materials. All the demands for high efficiency in power plants lead to development of enhanced materials like martensite steels, austenitic steels, Ni-alloys, alloys that work in high temperature applications.

2. Heat resistant steels in power industry

Steels which are used at temperatures up to the recrystallisation temperature are called heat resistant steels. They are characterized with good creep strength at high temperature. The materials that meet the above criteria are the ferritic (martensitic, bainitic) steels and austenitic steels. In table 1 is given the classification of creep resistant steels. The ferritic and martensitic steels have body-centered cubic crystal structure and in the iron is added chromium as one of the methods for improvement in high-temperature creep resistance and creep strength of steels used in power industry. Also adding alloy elements such as molybdenum, vanadium, niobium and nitrogen to improve their heat resistance [2].

Martensitic steels with chromium addition up to 12% are used for elements in construction that can withstand higher pressure and higher service temperature for application up to 650°C. Over 650°C are used austenitic steels that have nickel added to the iron-chromium composition and the alloy changes his body-centered cubic crystal structure to face-centered cubic crystal structure. In comparison, austenitic steels have highly strength and ductility, greater creep-rupture strength than martensitic steels. However, the

austenitic steels are much expensive than martensitic steels for their high contents of alloy element additions.

Chromium is added for oxidation resistance, high temperature strength and carburization resistance. Nickel is added to increase ductility, high temperature strength and resistance to carburization and nitriding. With adding element nickel the atomic structure becomes austenitic.

Table 1: Classification of creep resistant steels

Heat-resistant steels and special materials				
Bcc structure (body-centered cubic)				Fcc structure (face-centered cubic)
Up to 400°C	Up to 500°C	500 to 600°C	600 to 650°C	Above 700°C
Unalloyed	Alloyed		High-alloyed	
Ferritic-pearlitic steels, fine-grain structural steels	Mo- alloy steels	Bainitic (martensitic) ferritic steels	Martensitic 9 to 12% chromium steels	Austenitic steels, Ni and Co-materials
P235GH	16Mo3	13CrMo4-5	X10CrMoVNb9-1	X8CrNiNb16-13
P355NH	18MnMo4-5	10CrMo9-10	X22CrMoV12-1	X8NiCr32-20
No extra proven methods; higher purity; fine grain	Tr-increase through molybdenum alloying	Carbide/nitride formation + tempering	Precipitation hardening + spec. heat treatment	Fcc structure with high crystal recovery temperature

In this paper the emphasis is on martensitic steel type P91 and austenitic steel type 304H. For example, for boiler components materials, the austenitic steel 304H is used for boiler super heater tubes, elements that are experiencing 630°C and for steam headers and piping is used martensitic steel P91. The heater tubes need to be welded with the steam headers, that is why the need for dissimilar welds become necessary.

A dissimilar metal weld (DMW) is when grades with different chemical compositions are welded together. In fossil-fired power plants dissimilar metal welds are very common in the present. Austenitic stainless steel attachments welded onto ferritic steel tubes and pipes, stainless steel thermowells or steam sampling lines in ferritic steel pipes. On figure 1 is shown the possible combination of materials used and the fabrication techniques and welding processes involved in the fabrication of a steam boiler component [3].

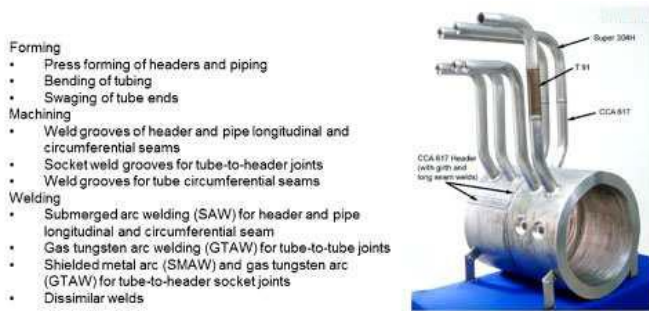


Fig. 1: Combination of materials, fabrication techniques and welding processes in fabrication of steam boiler [3]

3. Welding of heat resistant steels

Heat resistant steels with its strength at high temperatures needs to have sufficient resistance to creep processes. Creep usually occurs at high temperatures, where plastic deformation of materials takes place well below its yield strength under prolong stresses.

The dissimilar welded joints, used in piping systems, always represent a critical place in the system, in terms of possible occurrences of defects. The creep takes significant role in failure of these weld joints since it is the main cause of failure at elevated temperatures [4]. The dissimilar welded joints between martensitic and austenitic steel are often used in energy and process industry for new and refurbishment of existing plants. For creation of this type of joints and creation of weld with acceptable structural characteristics all recommendations and parameters of the welding process and heat treatment needs to be followed.

Matching filler metals for the new heat resistant steels and their great properties at elevated temperatures have been developed and qualified for all commonly used welding processes.

According to the different chemical composition of the materials for creation of dissimilar joint, one of the materials will encounter the carbon diffusion due to the difference in Cr content. Carbon moves from the material with low Cr content to material with high Cr content. The decarburization zone can be avoided with the use of nickel-base filler metal (fig.2), since carbon does not diffuse into the nickel-base material, using welding parameters such as preheating, and post weld heat treatment (PWHT) suitable to P91 [2].

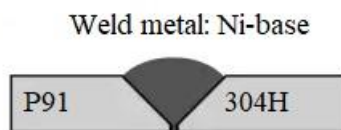


Fig. 2 Dissimilar weld between martensitic and austenitic steels

After 1970s, in research carried out by Electric Power Research Institute (EPRI) and other organizations, an increasing number of dissimilar metal welds in superheater and reheater tubes were fabricated as fusion welds using nickel-based filler metals, such as INCO 82, INCO 182 etc. The technical purpose for the switch to the nickel-based filler metals was the improved compatibility in thermal-physical properties with the lower alloyed materials [5].

Heat-resistant steels can be welded with use of various arc welding processes. In most cases, manual metal arc welding and tungsten inert gas welding are used. With tungsten inert gas welding of chromium-alloyed materials special attention must be dedicated to shielding the weld root, for this argon is suitable as a shielding gas.

To maintain and assure quality welds special attention should be dedicated to temperature time cycle of steel P91 as shown in figure 3 [6]. All heat treatment operations are a key factor when welding

P91 steel for obtaining the required toughness and creep resistance. An extremely well controlled preheat, interpass temperature and PWHT are mandatory to ensure that the required creep rupture properties and toughness are obtained in the weldment.

The time at temperature for PWHT depends on the thickness of the part. The PWHT temperature should also be controlled so that the formation of austenite, which would result in the formation of untempered martensite, is avoided.

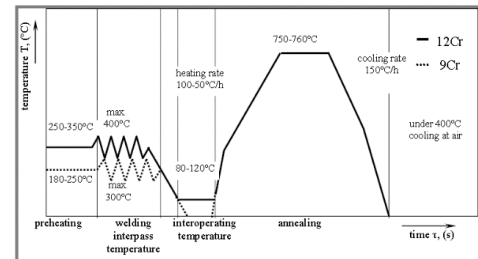


Fig 3: Temperature time cycle during welding of martensitic 9 or 12% chromium steels [6]

On fig. 4 [7] is shown a reduction in dimensions of structural components used in power plant for work at elevated temperatures. The use of P91 results in lower costs by reducing the mass of the structure and the labor. The design parameters are: design pressure 280 bar and design temperature 550°C.

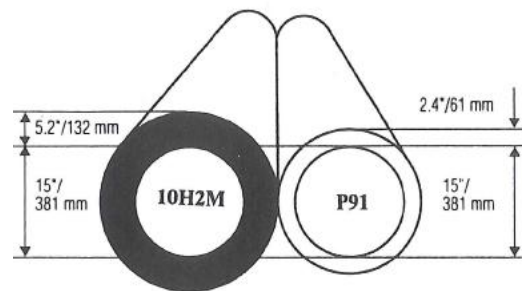


Fig.4: Wall-thickness of pipes used for same design parameters [7]

When it comes about welding P91 certain welding procedures and specification needs to be managed. Creep strength martensitic steels are highly hardenable, and upon cooling after welding, they undergo phase transformation that results in a fully martensitic structure. To obtain the desired properties the welds must undergo PWHT and an interpass temperature must be maintained. All the welding procedures and recommendation needs to be fulfilled to obtain quality welds and avoiding failures in the fossil fired power plants [8].

P91 is used for heavy sections such as pipes and headers in the advanced fossil fired power plants and austenitic stainless steel 304H is candidate steel for superheaters and reheater pendants, where the temperature is high. The best way of joining and producing quality welds is TIG process [9]. Current dissimilar metal welds involve buttering one end of the base metal with a suitable filler metal, PWHT and joining to the other base metal. The buttering is used to deposit surfacing metal on the base metal surface to provide compatible weld metal for the subsequent completion of the weld (fig. 5) [10].

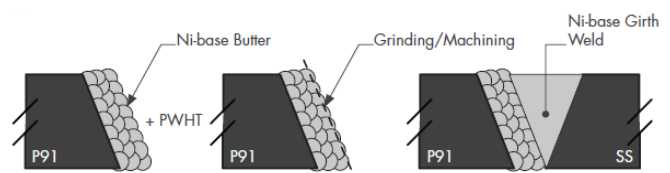


Fig. 5: Buttering of P91 steel [10]

In the EPRI publication (11) several weld metal composition and choice of welding process is considered. The composition

ranges differ for several elements but significant are nickel and manganese which influence on critical temperatures such as Ac1, Ms and Mf. The base metal specification allows maximum of 1% (Ni + Mn) whereas it is possible to have much higher levels in filler metal. When Ni+Mn reaches 1.4% the Ac1 decreases to 780°C, The Ms decreases below 350°C and Ms decreases below the required preheat temperature of 200°C. Cooling the weldment to room temperature prior to the PWHT is one way to avoid the formation of fresh martensite after PWHT. For good toughness in the weld seam, it is desirable to aim towards high nickel contents.

The filler material is mainly nickel based alloys which provide transition in coefficients of thermal expansion as well as proven to be beneficial for stopping the carbon diffusion from ferritic to austenitic side compared with conventional austenitic base filler [12].

4. Defects in Dissimilar Metal Welds

The dissimilar welded joints between martensitic and austenitic stainless steel always represent a critical place in the system, in terms of possible occurrences of defects. The chemical composition gradients (tab. 2) present unique issues relative to their design, behavior and life management especially operating at elevated temperatures.

Tab.2: Chemical composition of base metals and filler material (in wt.%)

	BM P91	BM 304H	FM Thermanit Nicro 82
C	0.08 ÷ 0.12	0.04 ÷ 0.08	0.02
Mn	0.30 ÷ 0.60	max. 2.00	3.0
Si	0.20 ÷ 0.50	max. 1.00	0.1
P	max. 0.015	max. 0.035	
S	max. 0.010	max. 0.015	
Cr	8.00 ÷ 9.50	17.00 ÷ 19.00	20.0
Ni	max. 0.40	8.00 ÷ 11.00	>67.0
Mo	0.85 ÷ 1.05		
V	0.18 ÷ 0.25		
Al	Max. 0.04		
Nb	0.06 ÷ 0.10		2.5
N	0.03 ÷ 0.07	max. 0.11	
Fe	Bal.	Bal.	<2

Failure mechanisms were noticed in thicker section between dissimilar weld with austenitic steel. For joining these two different materials, nickel base alloy filler material is used applying all the recommended welding parameters, preheat, interpass and PWHT for P91 steel. In EPRI report [13] where documented service experience of thick section of grade 91 in dissimilar welds. The most common failure has been cracking along the weld fusion line between grade 91 and the nickel base weld metal presented on fig. 6 [13].

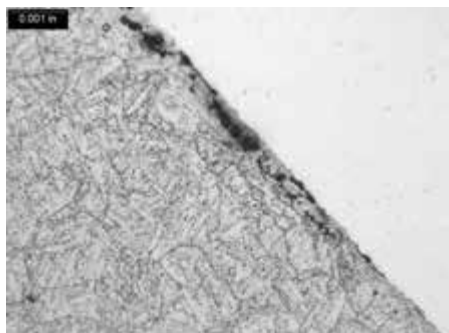


Fig. 6: Failure in grade 91 in DMW with nickel base weld metal [13]

The premature failures are creep related, occurring in short service life duration of the weld and typically along the grade 91 to nickel-base weld metal fusion line. There is a need for research work between dissimilar welds of P91 steel and 304H stainless steel because of increased demand for this type of joints in ultra-super critical power plants because of their better performance [14]. For accurate prediction of weld joints, its accuracy in service life is essential. Therefore, special attention needs to be paid to creep phenomenon which occurs at elevated temperatures, applying PWHT in acceptable range of annealing temperature which contribute to accelerate damage during service and results in type IV cracking. The degraded microstructure of the dissimilar welded joints is seen occurring within HAZ on the P91 steel side [15].

5. Conclusion

When joining metals with different chemical compositions and metallurgical properties of importance is the welding technology with particular attention paid to filler metal chemistry and PWHT. Tungsten inert gas (TIG) welding is the most preferred method for joining these two metals, it gives a strong weld with the required parameters.

As coal fired power plants will remain major source of energy it is necessary to research in improvement in plant efficiency and reduction of carbon footprint. New materials with better high temperature creep properties are developed and special attention should be paid on the selection of a suitable welding process and the performance of a suitable welding technology. Because of the good great properties at elevated temperatures and their applications in ultra-super critical power plants needs to predict creep failure controlling mechanism for better performance of the power plant fulfilling the requirement for higher efficiency and clean energy.

6. References

1. Viswanathan, R., Henry, J.F., Tanzosh, J. et al., U.S. program on materials technology for ultra-supercritical coal power plants. J. of Mater Eng and Perform 14, 281–292 (2005)
2. Tasak E., Ziewiec A.: Weldability of construction materials. Volume 1. Weldability of steels, Wydawnictwo JAK – Krakow 2009.
3. R. Viswanathan, R. Purgert, S. Goldstine, J. Tanzosh, G. Stanko, J. Shingledecker and B. Vitalis: Proc. 5th Int. Conf. on 'Advances in materials technology for fossil power plants', Marco Island, FL, USA, October 2007, 1–15
4. S. Chaudhuri, NML Jamshedpur 831007, India, 2008, pp. 85–114
5. EPRI report 2008, Report 1015699
6. J. Pecha, D. Stano, O. Peleš, Welding of 9% Cr creep resisting steels for power Engineering equipment, Zavarivanje i zavarene konstrukcije (4/2004), str. 159–168
7. The success of a new material P91/T91 steel enhances power station efficiency, Mannesmann Rohrwerke report, S28/29
8. W. F. Newell, Jr.: 'Welding and post weld heat treatment of P91 steel', Weld. J., 2010, 33–36.
9. Echezona, Nnamdi & Akinlabi, Stephen & Jen, Tien-Chien & Fatoba, Olawale & Hassan, Sunir & Akinlabi, E.. (2021). Tig Welding of Dissimilar Steel: A Review. 10.1007/978-981-16-3641-7_1.
10. T. Totemeier, Dissimilar Metal Welds in Grade 91 Steel, Structural integrity 2018, volume 44, pg15–18
11. Coleman K, Gandy D. Guideline for welding P(T) 91, document 1006590, EPRI, 1300 W.T. Harris Blvd., Charlotte, NC 28262, USA; 2002
12. J.M. Rase, Carbon Diffusion Across Dissimilar Steel Welds 1992
13. EPRI report 2014, Report 3002006759
14. Krstevska, Aleksandra & Poser, Maja & Zdravski, Filip. (2022). WELDABILITY BETWEEN STEEL TYPE 304H AND STEEL TYPE P91 FOR HIGH TEMPERATURE APPLICATIONS.
15. A Zielinski, G Golanski, P Urbanczyk, J Slania, J Jasak, Microstructure and properties of dissimilar welded joint between p91 and tp347hfg steels after 105 000 h service, Prace IMZ 1 2015

Visualization and analysis of gear drives parameters with the help of computer-aided mathematics systems

Svetlin Stoyanov
University of Ruse "Angel Kanchev", 8 Studentska str., POB 7017, Ruse, Bulgaria
SStoyanov@Uni-Ruse.BG

Abstract: The visualisation capabilities of the main software systems for computer-aided mathematics are reviewed. The advantages of the software system Matlab are described. The system is appropriate when visualization and analysis of engineering data are required. The author sets out to highlight the three-dimensional graphics and optimization synthesis of gear drives.

Keywords: THREE-DIMENSIONAL GRAPHICS, COMPUTER-AIDED MATHEMATICS, SOFTWARE SYSTEMS, MATLAB, GEAR DRIVES, LOAD CAPACITY, EFFICIENCY COEFFICIENT, MAXIMAL TORQUE

1. Overview of the visualization capabilities of the leading systems for computer-aided mathematics

The contemporary growth of software systems provides powerful new opportunities in all areas of engineering and science. For example, in [14] is presented a study about applications of leading software systems for piezoelectric beams investigations. The development of extremely low power electronics and wireless systems has led to a strong interest in the fields of energy harvesting and development of miniature generators. Typically, these devices are used to power sensors and wireless communication systems, enabling standalone wireless sensors that are cheap to deploy. In the area of the mechanical structure vibrations investigations and the multiphysics simulations, four software systems have the lead positions. These are: **ABAQUS**, **COMSOL**, **SolidWorks**, and **MATLAB**. The software system **MATLAB** is a system for "computer aided mathematics" and "matrix laboratory", but in fact this software system is often used from scientist and engineers to solve mathematical models that describes problems in the area of the mechanical structure vibrations and the multiphysics simulations.

In [11, 12, 18] are presented selected investigations of structure vibrations conducted with the help of contemporary mechanical engineering software systems. Also, in [1, 11, 13, 14] are described investigations on gear transmissions performed with the finite element method in the integrated working environment of the system **ABAQUS**.

In addition to studies described above, in this work the author set out to highlights the visualization capabilities of the leading systems for computer-aided mathematics: **MATLAB**, **Wolfram Mathematics**, and **Maple**.

1.1. Wolfram Mathematics

Wolfram Language provides powerful functions that automate the process of creating cognitively and aesthetically compelling representations of structured and unstructured data. This is valid not only for points, lines, and surfaces, but also for graphs and networks. This is available due to many original algorithms developed at **Wolfram Research**.

On Fig. 1 and Fig. 2 are shown some examples for the visualization capabilities of **Wolfram Mathematics** [5, 6].

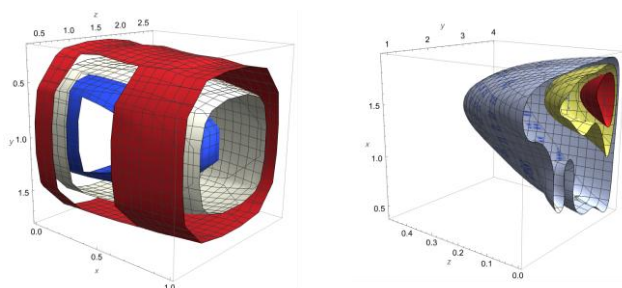


Fig. 1. Boundaries and solutions of partial differential equations

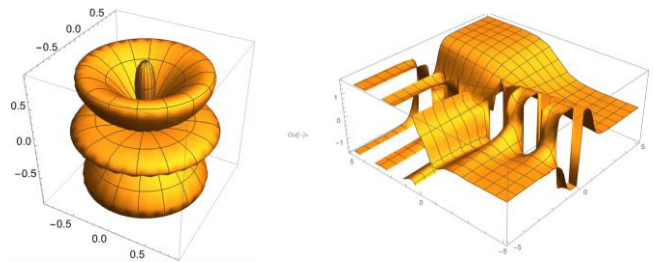


Fig. 2. Spherical 3D graph and plot of a function with singularities

1.2. MATLAB

The name "**MATLAB**" comes from **MATRIX LABORATORY** and has been chosen because of the powerful capabilities of this software system for working with matrices. Using this, the system **MATLAB** solves the problem of visualization of three-dimensional data in one. The data is plotted on a three-dimensional mesh with point size showing value of it. Edge color changes via z axis to distinguish coordinate of points easier. One can compare sets of data, track changes in data over time, or show data distribution. Also, the plots can be created programmatically using graphics functions or interactively using the *Plots tab* at the top of the **MATLAB** desktop.

Software system **MATLAB** includes a tool with graphical user interface (GUI) for data interpolation – Fig. 3. This together with the discussed in the next paragraph optimization capabilities gives richest abilities to build automatized software for optimization and design of gear transmissions [2, 3, 19, 20].

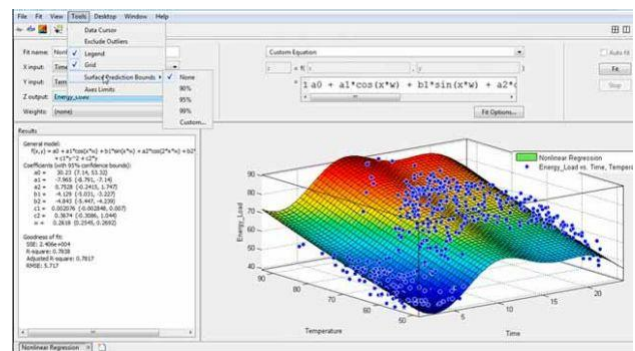


Fig. 3 An example picture from MATLAB interpolation GUI

MATLAB Optimization Toolbox provides functions for finding parameters that minimize or maximize objectives while satisfying constraints [4, 7]. The toolbox includes solvers for linear programming (LP), mixed-integer linear programming (MILP), quadratic programming (QP), second-order cone programming (SOC), nonlinear programming (NLP), constrained linear least squares, nonlinear least squares, and nonlinear equations.

Optimization problems can be defined with functions and matrices or by specifying variable expressions that reflect the

underlying mathematics. One can use automatic differentiation of objective and constraint functions for faster and more accurate solutions.

The toolbox solvers can be used to find optimal solutions to continuous and discrete problems, perform tradeoff analyses, and incorporate optimization methods into algorithms and applications. Also, **MATLAB Optimization Toolbox** gives abilities to perform design optimization tasks, including parameter estimation, component selection, and parameter tuning.

1.3. Maple

Maple is a software tool that combines a powerful mathematics engine with an interface that makes it easy to manage calculations. It provides an environment that can maximize the value of calculation efforts. With Maple, one can easily validate, document, retain, reuse, and modify your calculations, reducing risk while saving time and effort in both current and future projects.

As **MATLAB** provides simulation environment named **SimScope**, **Maple** has a tool named **MapleSim**. It gives ability to simulate the dynamics of diverse physical systems, including mechanical systems. This is illustrated on Fig. 4 as an indicator for the visualization capacities of **Maple**.

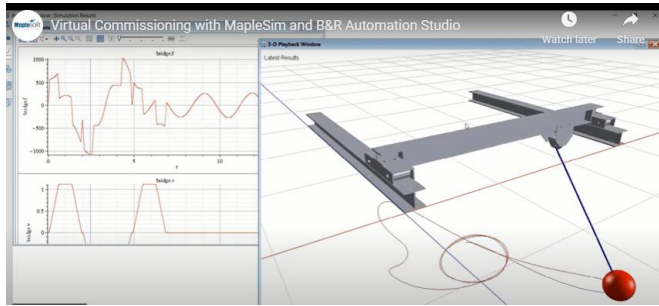


Fig. 4. Virtual commissioning with MapleSim and B&R Automation Studio

MapleSim has libraries with mechanical elements, for example bodies and joints. But these elements are idealized – the bodies are rigid and non-deformable, and the joints are without energy losses or with linear energy losses model. So, this is suitable for engineering tasks, but is insufficient for scientific investigations. In these cases, the systems **ABAQUS** or **ANSYS** are usually used [11, 15, 16, 18].

1.4. Conclusions

It can be concluded that, the software systems **MATLAB**, **Wolfram Mathematics**, and **Maple** have approximately equal three-dimensional plotting capabilities. The difference is that the system **Wolfram Mathematics** can be labeled as more mathematic scientists orientated, than the **MATLAB**, which is more suitable for machine engineers and scientists. Also, while other programming languages usually work with numbers one at a time, **MATLAB** operates on whole matrices and arrays. Along with that **MATLAB** is one of the best choices when optimization needs to be done [1].

For the reasons described above, the **MATLAB** was chosen for the purposes of this investigation.

2. Description of the developed software

To interpolate and visualize the calculated in [8, 9] data, a software in the integrated working environment of the system **MATLAB** is developed. This gives two new abilities, as follows:

- ⇒ An ability to directly signify the relations between three parameters (or even between four parameters, if the color in set as independent indicator);
- ⇒ An ability to render relations in uninterrupted three-dimensional space (or even in four-dimensional space, if the color in set as independent indicator).

A generalized flow-chart of the developed software is presented on Fig. 5. It follows a description of each step of the flow-chart.

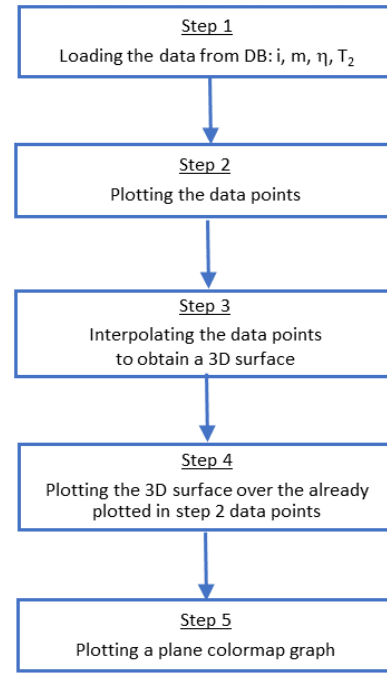


Fig. 5. A flow-chart of the the developed software

Step 1: Loading the input data. The input data is structured as a table with colons for: gears module m , transmission ratio i , coefficient of the efficiency η , and output torque T_2 . The data can be loaded from plain text files, binary **MATLAB** files (*.mat) or from **Excel** datasheets.

Step 2: Plotting the data points. On this step, the software visualizes 3D coordinate system, label the axis with corresponding notations, set the axis limits and increment, and visualize appropriate grid. Then, the data points are plotted as solid red points – Fig. 6.

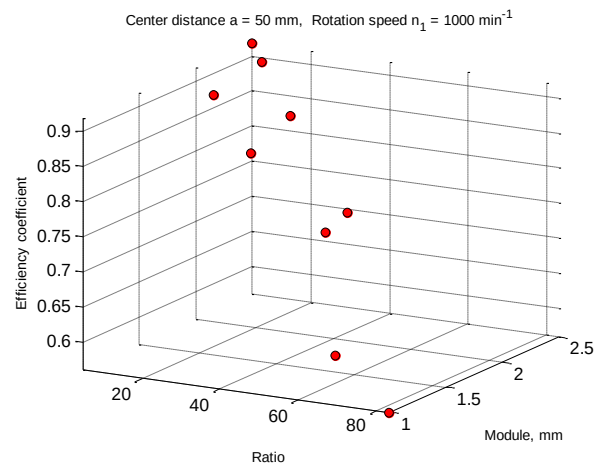


Fig. 6. A 3D plot of the data points loaded

Step 3: Interpolate the data points. The function **interp3** of the system **MATLAB** is used. The function syntactic is:

$$Vq = \text{interp3}(X, Y, Z, V, Xq, Yq, Zq),$$

where: Vq contains the interpolated values of a function of three variables at specific query points using linear interpolation. The results always pass through the original sampling of the function; X, Y , and Z contains the coordinates of the sample points; V contains the corresponding function values at each sample point;

Xq, Yq , and Zq contains the coordinates of the query points.

Step 4: Plotting the 3D surface. On this step, the surface obtained is superimposed on the data points plotted in Step 2. Also, a legend is visualized – Fig. 7.

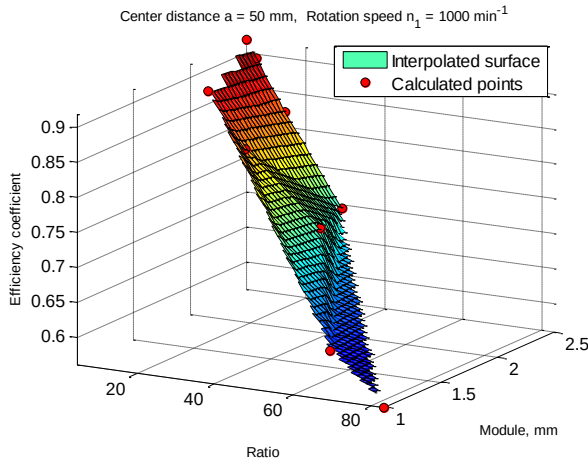


Fig. 7. Efficiency coefficient in relation from ratio and module

Step 5: Plotting a plane colormap graph. On this step, a new figure is plotted – Fig. 8. It is a plane graph – the efficiency coefficient values are indicated with a color map starting from dark blue and ending with dark red color.

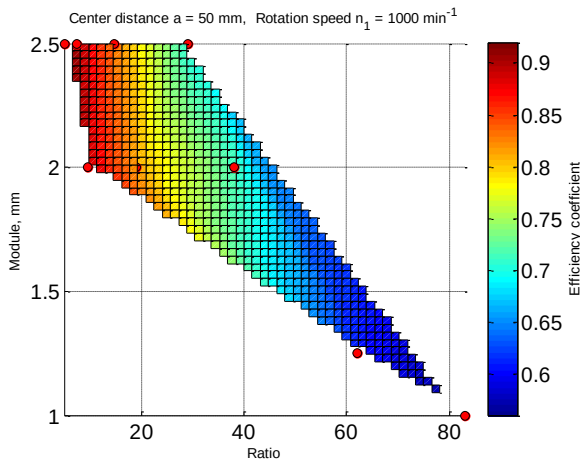


Fig. 8. Color map representation

In combination with computer-aided design software, the software developed gives an ability the investigation to be continued with development of an automatized optimization and design system. This can be done in the integrated working environment of the software systems **MATLAB** and **SolidWorks**.

MATLAB also provides some frequently used minor capabilities, for example: saving the graphs created to image files, save the numerical results in plain text format or binary format files, export the results to MS Excel software, etc.

3. Results

The graphical visualizations obtained with the software created are presented and analyzed completely in [17]. In this paper, selected results are presented on the following figs. On Fig. 9 is shown a surface with a data point lower than other points in the plane interpolated surface. That is in the top left corner, i.e., in the area with higher values of the efficiency coefficient. From Fig. 9, it can be observed that the efficiency coefficient increases with the increase of the module and the decrease of the ratio.

The software system **MATLAB** gives the ability multiple three-dimensional surfaces to be superimposed. On Fig. 10b are presented two three-dimensional relations together for center distance $a = 63$ mm and rotation speed $n_1 = 1500$ min⁻¹. With this approach, one plot can represent the dependence of the efficiency coefficient from

the ratio and module, and at the same time from the ratio and output torque. From Fig. 10, it can be observed that efficiency coefficient grows with decreasing the output torque and the ratio.

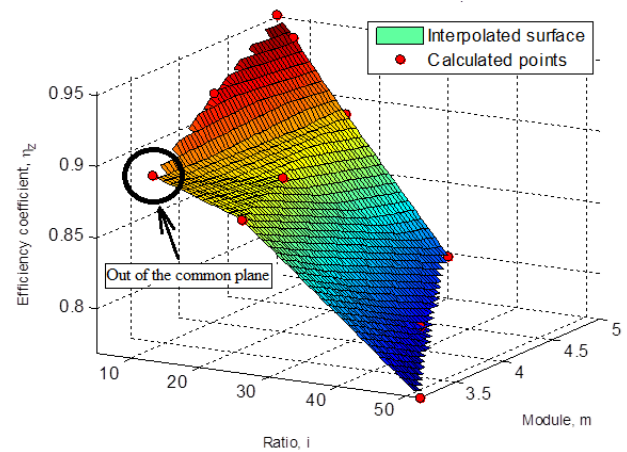


Fig. 9. Efficiency coefficient in relation from ratio and module for center distance $a = 100$ mm and rotation speed $n_1 = 1500$ min⁻¹.

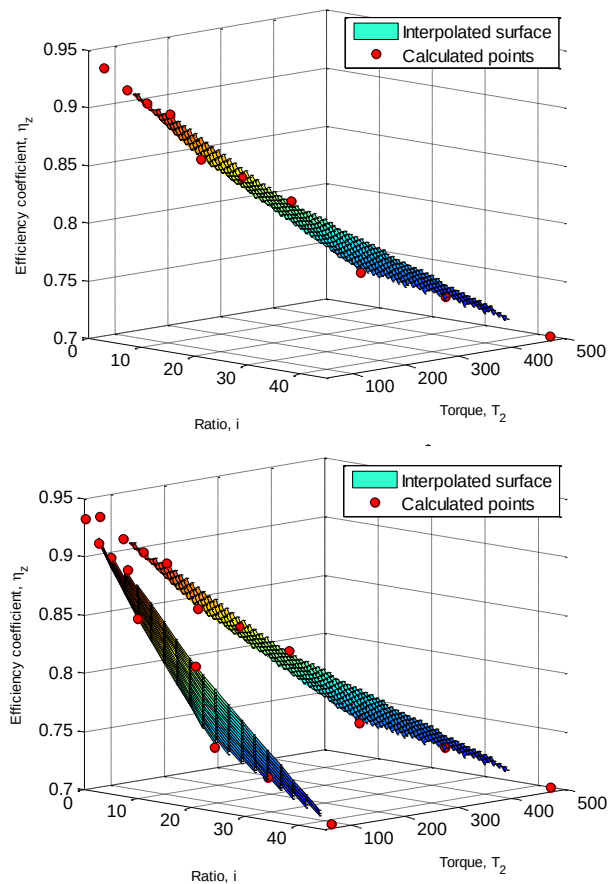


Fig. 10. Efficiency coefficient for center distance $a = 63$ mm and rotation speed $n_1 = 1500$ min⁻¹: a – efficiency coefficient in function of ratio and torque; b – with superimposed surface of efficiency coefficient in function of ratio and module.

4. Conclusions

The capabilities of the main software systems for computer-aided mathematics are reviewed. In this work the author set out to highlights the visualization capabilities of the leading systems for computer-aided mathematics: **MATLAB**, **Wolfram Mathematics**, and **Maple**.

It can be concluded that, the software systems **MATLAB**, **Wolfram Mathematics**, and **Maple** have approximately equal three-

dimensional plating capabilities. The difference is that the system **Wolfram Mathematica** can be labeled as more mathematic scientists orientated, than the **MATLAB**, which is more suitable for machine engineers and scientists. **MATLAB** is a programming and numeric computing platform used by millions of engineers and scientists to analyze data, develop algorithms, and create models. It combines a desktop environment tuned for iterative analysis and design processes with a programming language that expresses matrix and array mathematics directly. Also, **MATLAB** includes the *Live Editor* for creating scripts that combine code, output, and formatted text in an executable notebook. In this work the author set out to highlight the visualization capabilities, so it is important that the **MATLAB** provides built-in libraries for visualizations. The built-in plots can be used to visualize engineering data, gain insights, and identify underlying patterns and trends. One can choose from the relevant plots presented, based on the selected data. This lets the optimal visualization to be done.

For the reasons described above, the **MATLAB** was chosen for the purposes of this study. Then, software for data interpolation and three-dimensional visualization are developed. The software is oriented to gear drives. Therefore, this investigation is continued in [17], where visualization and analysis of worm gear drives efficiency and load capacity are performed. This includes 3D graphical representation of the efficiency coefficient and maximal torque values for several combinations of modules, ratios, center distances, etc. Also, in [17] important conclusions are made, for example that the efficiency coefficient increases with the increase of the module and the decrease of the ratio.

3. References

1. A. Dobрева, S. Stoyanov. Optimization Research of Gear Trains with Internal Meshing. Ruse, University Publishing Centre, pp 144 (2012)
2. A. Pillai, A. Ray, S. Kaul. Design optimization of spur gear using genetic algorithm. International Conference on Design, Automation, and Control (2020)
3. A. Messac. Optimization in Practice with MATLAB®: For Engineering Students and Professionals 1st Edition. Cambridge University Press (2015)
4. C. Lopez. MATLAB Optimization Techniques. Springer, ISBN 978-1-4842-0292-0 (2014)
5. C. Hastings, K. Mischo, M. Morrison. Hands-on Start to Wolfram Mathematica and Programming with the Wolfram Language, 3rd ed. Edition, Wolfram Media Inc (2020)
6. D. Bahns, W. Bauer, I. Witt. Quantization, PDEs, and Geometry: The Interplay of Analysis and Mathematical Physics – Operator Theory: Advances and Applications, 1st ed., Birkhauser, (2016)
7. D. Valentine, B. Hahn. Essential MATLAB for Engineers and Scientists 7th Edition. Springer ISBN 978-1-4842-0292-0 (2018)
8. G. Mollova, A. Dobрева. Improving load capacity parameters of worm gears. MATEC Web of Conferences 366, 02002 (2022)
9. G. Mollova, V. Dobrev. Design methodology for investigating worm gear transmissions with significant dimensions. IN: Proceedings of University of Ruse, Vol 60, ISSN: 1311-3321, pp. 41-47, (2021)
10. J. Wu, L. Shu, X. Wang. Research on the Integrated Development System of NGW Planetary Gear Transmission. Applied Mechanics and Materials, Vol 109, pp. 355-359 (2011)
11. S. Stoyanov. Vibration measurement and analysis of a friction stir welding process. Proceedings of University of Ruse, volume 61, pp. 47-52 (2022)
12. Stoyanov S. Software tools for mechanical structures resonant frequencies determination: Vibration signal processing for modal analysis. ACM International Conference Proceeding Series (2018)
13. S. Stoyanov, A. Dobрева. Systems Analysis and Design of Gear Drives through Innovative Software Approach. IEEE Xplore:

5th International Symposium on Multidisciplinary Studies and Innovative Technologies (2021)

14. S. Stoyanov. Applications of contemporary software systems for piezoelectric beams investigations. International Scientific Journal "Industry 4.0" (2020)

15. S. Stoyanov, V. Dobrev, A. Dobрева. Finite Element Contact Modelling of Planetary Gear Trains. Material Science and Engineering, IOP Publishing (2017)

16. S. Stoyanov, V. Dobrev, A. Dobрева. Investigating Dynamic Behavior of Planetary Gear Trains through the Systematic Approach. VDI Verlag GmbH Duesseldorf VDI Berichte (2017)

17. S. Stoyanov, G. Mollova. Visualization and analysis of worm gear drives efficiency and load capacity. XX Jubilee International Congress – Machines, Technologies, Materials, winter session, Borovets, Bulgaria (2023) (to be published)

18. S. Stoyanov. An experimental setup for determination of the resonant frequencies of a mechanical frame structure. Fundamental Sciences and Applications, Journal of the Technical University – Sofia, Plovdiv branch, Bulgaria, ISBN: 1310-8271 (2018)

19. U. Amatya, B. Prajapati. Development of MATLAB Based Software for Simple Spur Gear Design and its Validation for Stress Simulations. Proceedings of 8th IOE Graduate Conference, Vol. 8, pp. 209-215 (2020)

20. V. Babu, M. Majumder, A. Ramprasad. Involute Tooth Spacing, Gear Profile and 3D Gear development with MATLAB® Graphical User Interface and Solidworks. International Journal of Industrial Engineering (2018)

Basic Analytical and Geometric Synthesis of Conic Convolute Helical Surfaces of Spatial Rack Drives. Software and Graphic Study

Emilia Abadjieva^{1,2}

Institute of Mechanics- Bulgarian Academy of Sciences, Acad. G. Bonchev Str, block 4, Sofia, Bulgaria¹

Center of Competence MIRACLe – Mechatronics Clean Technologies, Sofia, Bulgaria²

abadjieva@gmail.com

Abstract: This study treats a study oriented to the basic synthesis of the conic convolute helicoid. On the base of the elaborated mathematical model, the written equations show a theoretical possibility, depending on the basic geometrical characteristics of the designed conic convolute worm, to generate the active flanks of the helical teeth as parts of these conic convolute helicoids. Analytical dependences of the cross-section and the axial section of the conic convolute surfaces are obtained. These relations, as well as the performed studies of the graphic images of these sections, precede the process of constructing the algorithms for computer synthesis and design of these conic helical surfaces. The realized studies of the graphic images of these sections are the basis of the algorithms for computer synthesis and design of these conical helical surfaces. The appearance of singular points on these surfaces is examined, which is of particular importance for their technological synthesis. Based on the developed algorithm, a computer program for the synthesis and visualization of conic helical surfaces is realized and illustrated.

Keywords: SPATIAL RACK DRIVES, CONIC LINEAR HELICOIDS, GEOMETRIC CHARACTERISTICS

1. Introduction

In the group of gear mechanisms, a certain significance for the technique has spatial rack mechanisms, transforming motions of type $(R \leftrightarrow T)$ [1]. The reason for this is that, as a mechanical system, this type of gear drives does not have an alternative for cases of motions' transformation with high power, as there are an alternative for small power and displacements, which are electrical drives with electronic control. Hydraulic transmissions represent a definite alternative, but high-tech and expensive servo systems are used to achieve high positioning accuracy.

The successful implementation of the spatial rack drives with new kinematic and strength characteristics into the techniques is retained by the insufficient studying of the general principles of this transformation, due to the lack of offered specific approaches to mathematical modeling, oriented to their synthesis.

The global structure of every mathematical model of the above-considered type is determined by [1-3]:

- The designation of the three-link mechanism under the preliminary defined law of motions transformation;
- the placement of the characteristic axes of the movable links and the nature of the conjugation of the elements of high kinematic joints (with a point or linear tangential contact);
- the technological devices, connected with the choice of the geometry of the generating (instrumental) surfaces and the chosen principle for generation by T. Olivier.

Further below, two ways of generation of the active tooth surfaces Σ_2 of the gear rack (link $i=2$) of the studied mechanism are marked [1 - 3]:

- Σ_2 is generated by enveloping in accordance with the second principle of T. Olivier; Σ_2 is cut with an instrument J , which generating (enveloping) surfaces Σ_j are geometrically identical with the tooth surfaces Σ_1 of the rotating link $i=1$, i.e. $\Sigma_j \equiv \Sigma_1$; the cutting instrument J occupies the same relative placement towards the blanks of the link $i=2$; the relative motion of the instrument J towards the blank of the link $i=2$ is the same as it is of Σ_1 towards Σ_2 when there are work mating. Hence, the generated surfaces Σ_2 have a line contact with Σ_1 .

- Σ_2 is a cylindrical surface, for which it is easy to determine the analytical type of its normal section, which is the normal profile of the tooth of the gear rack. When the orientation of the longitudinal line of the tooth and the geometry of its normal profile are known, then Σ_2 can be generated by copying. In this case also Σ_1 and Σ_2 contact in a line.

In the current study, the first approach to the synthesis of these motions' transformers is applied. This determines the importance of the written here theory, which is referred to the synthesis of the surfaces $\Sigma_j \equiv \Sigma_1$ of the conic linear helicoids.

To realize a complete study of the conic convolute helical surfaces are written analytical descriptions of their cross-sections and axial sections. Other important characteristics of the technological synthesis of the spatial rack drives are the conditions for the appearance of singular points on the conic linear helical surfaces. In the study, this topic is briefly explained.

2. Synthesis of Conic Linear Helical Surfaces

Generation of Conic Convolute Mechanisms. The helicoids and especially the linear helicoids are widely applied as active tooth surfaces of spatial transmissions with crossed axes, both in work meshing and instrumental meshing conditions. Such choice of the active tooth surfaces for these gears is determined by technological manufacturing, especially when their synthesis is realized under the second Oliver's principle [1, 4 - 7]. In many cases (like the manufacture of the cylindrical worm gear and Spiroid¹ and Helicon gear-set), these surfaces are the only alternative.

On Fig. 1 is illustrated the generation of right-handed conic convolute helicoids $\Sigma_i^{(j)}$ ($j=1, 2$) determined by different geometrical characteristics of the helical teeth (treads) of the particular gear mechanism [8 - 10]. The process of helical surfaces' generation is considered in a fixed coordinate system $S_p^{(j)}(O_p^{(j)}, x_p^{(j)}, y_p^{(j)}, z_p^{(j)})$ and it is as follows. The generatrix of $\Sigma^{(j)}$ doesn't cross the axis $O_p^{(j)}z_p^{(j)}$ which coincides with the geometric axis of the gear. $\Sigma^{(j)}$ and $O_p^{(j)}z_p^{(j)}$ conclude an angle $0,5\pi < \xi^{(j)} < \pi$. The line $L^{(j)}$ belongs to a plane $T^{(j)}$, which

¹ Spiroid and Helicon are trademarks registered by the Illinois Tool Works, Chicago, Ill.

is tangential to the directed circle cylinder $C^{(j)}$. The generation of the conic convolute helicoid $\Sigma_1^{(j)}$ by the line $L^{(j)}$ is realized by two generatrix motions [2, 8, 11]: axial helical motion along the longitudinal axis $O_p^{(j)}z_p^{(j)}$ with parameter $p_s^{(j)} = \text{const.}$;

crossed helical motion in the plane $\Sigma^{(j)}$, perpendicular to the axis $O_p^{(j)}z_p^{(j)}$ with parameter $p_t^{(j)} = \text{const.}$ Here, it will be noted that $\Sigma_1^{(1)}$ is conic convolute helicoid surface, which is oriented to the positive direction of the axis $O_p^{(1)}z_p^{(1)}$, and $\Sigma_1^{(2)}$ is the helicoid, turned along the negative direction of the $O_p^{(2)}z_p^{(2)}$.

The vector equation of the conic convolute helicoid surface $\Sigma_1^{(j)}$, in accordance with Fig. 1, has the form [1, 2, 11]:

$$\bar{\rho}_1^{(j)} = \bar{r}_0^{(j)} + \bar{s}^{(j)} + \bar{t}^{(j)} + \bar{u}^{(j)}, \quad (1)$$

where $\bar{\rho}_1^{(j)}$ is a radius-vector of a point $N^{(j)}$ that belongs to the conic convolute helicoid $\Sigma_1^{(j)}$; $\bar{r}_0^{(j)}$ - radius-vector of the directed cylinder $C^{(j)}$; $\bar{s}^{(j)}$, $\bar{u}^{(j)}$ - coordinates of the helical surface $\Sigma_1^{(j)}$; $\bar{s}^{(j)} = p_s^{(j)}\bar{g}^{(j)}$ - axial motion of the generatrix $L^{(j)}$; $\bar{t}^{(j)} = p_t^{(j)}\bar{g}^{(j)}$ - crossed displacement (tangential to the directed cylinder $C^{(j)}$) of the generatrix line $L^{(j)}$.

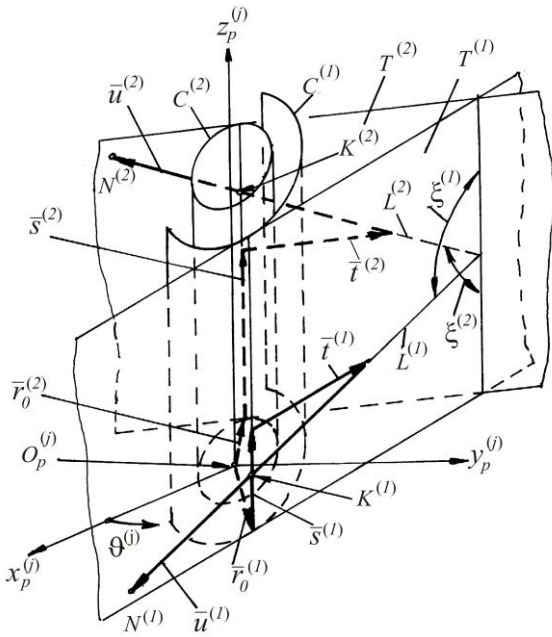


Fig. 1 Conic convolute helicoids generation

When (1) is written in a coordinate system $S_p^{(j)}$ it is obtained:

$$\begin{aligned} x_p^{(j)} &= r_0^{(j)} \cos \vartheta^{(j)} \pm A \sin \vartheta^{(j)}, \\ y_p^{(j)} &= r_0^{(j)} \sin \vartheta^{(j)} \mp A \cos \vartheta^{(j)}, \\ z_p^{(j)} &= p_s^{(j)} \vartheta^{(j)} \pm u^{(j)} \cos \xi^{(j)}, \\ A &= (u^{(j)} \sin \xi^{(j)} - p_t^{(j)} \vartheta^{(j)}), \end{aligned} \quad (2)$$

For equation systems (2) the upper signs and $j = 1$ refer to the $\Sigma_1^{(1)}$, and the lower and $j = 2$ refer to the $\Sigma_1^{(2)}$.

Substituting in (2)

$$R_0^{(j)} = u^{(j)} - \frac{p_t^{(j)} \vartheta^{(j)}}{\sin \xi^{(j)}} \quad \text{and} \quad (3)$$

$$p^{(j)} = p_s^{(j)} \pm p_t^{(j)} \cot \xi^{(j)}$$

it is obtained

$$\begin{aligned} x_p^{(j)} &= r_0^{(j)} \cos \vartheta^{(j)} \pm R_0^{(j)} \sin \xi^{(j)} \sin \vartheta^{(j)}, \\ y_p^{(j)} &= r_0^{(j)} \sin \vartheta^{(j)} \mp R_0^{(j)} \sin \xi^{(j)} \cos \vartheta^{(j)}, \\ z_p^{(j)} &= p^{(j)} \vartheta^{(j)} \pm R_0^{(j)} \cos \xi^{(j)}; \end{aligned} \quad (4)$$

Equation (4) represents the conic convolute helicoid surface $\Sigma_1^{(j)}$ as a cylindrical one with helical parameter $p^{(j)} = \text{const.}$ and coordinates $\vartheta^{(j)}$ and $R_0^{(j)}$. (The point $K^{(j)}$ is the accounting origin of coordinate $R_0^{(j)}$. $C^{(j)}$ and plane $T^{(j)}$ are contacting in this generatrix $L^{(j)}$). The point $K^{(j)}$ is considered as a point from the directed helical line $\bar{\rho}_0^{(j)} = \bar{\rho}_0^{(j)}(\vartheta^{(j)})$ on the $C^{(j)}$.

For the synthesis of the conic linear helicoids (conic convolute, conic involute, and conic Archimedean) are written three computer programs [1] with analogical (typified) structure and organization of the calculated process. Here and further, it is illustrated the application of these programs, when is realized computer synthesis and visualization of the three types of conic linear helicoids (see Fig. 2, Fig. 3, Fig. 4).

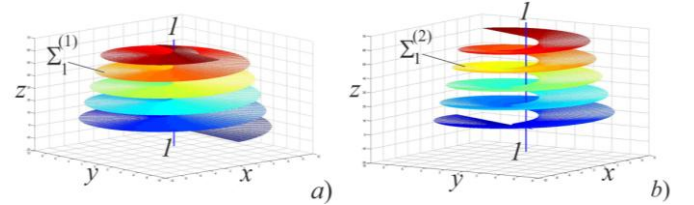


Fig. 2 Spatial conic convolute gear: a) conic convolute right-handed worm $\Sigma_1^{(1)} \Rightarrow \xi^{(1)} = 95^\circ$, $r_0^{(1)} = 0,90 \text{ mm}$; $u^{(1)} \in [0,10]$, $\vartheta^{(1)} \in [0,5\pi]$; b) $\Sigma_1^{(2)} \Rightarrow \xi^{(2)} = 125^\circ$, $r_0^{(2)} = 1,19 \text{ mm}$; $u^{(2)} \in [0,10]$, $\vartheta^{(2)} \in [0,5\pi]$

Conic involute helical surfaces generation. It is known [1, 2, 11] that each developable surface is a cylindrical one, conic one, or a locus of the tangent lines to an arbitrary curve and vice versa - each cylindrical, conic or a surface representing the locus of tangent lines to a curve is a developable surface.

The specific for each developable surface is, that the parameter of distribution is equal to zero, i.e.

$$h^{(j)} = p^{(j)} + r_0^{(j)} \cot \xi^{(j)} = 0, \quad \text{or} \quad (5)$$

$$\cot \xi^{(j)} = -\frac{p^{(j)}}{r_0^{(j)}}$$

After observing condition (5), equation (4) describes the conic involute helicoid (Fig. 3), which is given in the form:

$$\begin{aligned} x_p^{(j)} &= r_0^{(j)} \cos \vartheta^{(j)} \pm R_0^{(j)} \cos \lambda_0^{(j)} \sin \vartheta^{(j)}, \\ y_p^{(j)} &= r_0^{(j)} \sin \vartheta^{(j)} \mp R_0^{(j)} \cos \lambda_0^{(j)} \cos \vartheta^{(j)}, \\ z_p^{(j)} &= p^{(j)} \vartheta^{(j)} \mp R_0^{(j)} \sin \lambda_0^{(j)}, \end{aligned} \quad (6)$$

where $R_0^{(j)} = u^{(j)} - \frac{p_t^{(j)} \vartheta^{(j)}}{\cos \lambda_0^{(j)}}$, $p^{(j)} = p_s^{(j)} \mp p_t^{(j)} \tan \lambda_0^{(j)}$

and $\lambda_0^{(j)} = \xi^{(j)} - \pi/2$ is a spiral angle [1, 11] for the directed helical line on the cylinder $C^{(j)}$. In this case, the cylinder $C^{(j)}$ is called a basic cylinder.

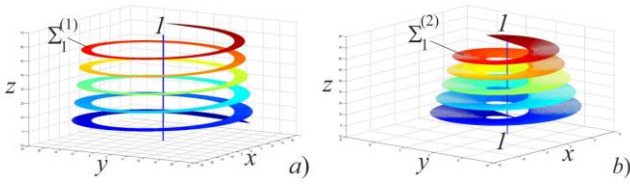


Fig. 3 Spatial conic involute mechanism: a) conic involute right-handed worm $\Sigma_1^{(1)} \Rightarrow \xi^{(1)} = 95^\circ$, $r_0^{(2)} = 18,40$ mm; $u^{(1)} \in [-5,15]$, $\vartheta^{(1)} \in [0,5\pi]$; b) $\Sigma_1^{(2)} \Rightarrow \xi^{(2)} = 125^\circ$, $r_0^{(2)} = 2,84$ mm; $u^{(2)} \in [-5,15]$, $\vartheta^{(2)} \in [0,5\pi]$

Conic Archimedean helical surfaces generation. The conic Archimedean helicoid is obtained when the generatrix $L^{(j)}$ (see Fig. 4) crosses the axis $O_p^{(j)} z_p^{(j)}$, i.e. when $r_0^{(j)} = 0$.

Then from (2), it is obtained:

$$\begin{aligned} x_p^{(j)} &= \pm(u^{(j)} \sin \xi^{(j)} - p_t^{(j)} \vartheta^{(j)}) \sin \vartheta^{(j)}, \\ y_p^{(j)} &= \mp(u^{(j)} \sin \xi^{(j)} - p_t^{(j)} \vartheta^{(j)}) \cos \vartheta^{(j)}, \\ z_p^{(j)} &= p_s^{(j)} \vartheta^{(j)} \pm u^{(j)} \cos \xi^{(j)}. \end{aligned} \quad (7)$$

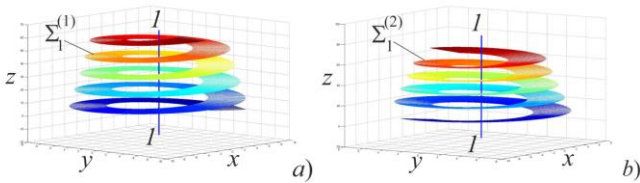


Fig. 4 Spatial conic Archimedean mechanism: a) conic Archimedean right-handed worm $\Sigma_1^{(1)} \Rightarrow \xi^{(1)} = 95^\circ$, $u^{(1)} \in [6,10]$, $\vartheta^{(1)} \in [0,5\pi]$; b) $\Sigma_1^{(2)} \Rightarrow \xi^{(2)} = 125^\circ$, $u^{(2)} \in [6,10]$, $\vartheta^{(2)} \in [0,5\pi]$

The curvilinear coordinate $\vartheta^{(j)}$ in (7) represents the angle on which rotates the normal vector $\vec{r}_0^{(j)}$ to the axial plane (determined by the $L^{(j)}$ and $O_p^{(j)} z_p^{(j)}$). If it is noted with $\vartheta_a^{(j)} = \vartheta^{(j)} + \pi/2$, the angle, that the plane $(L^{(j)}, O_p^{(j)} z_p^{(j)})$ concludes with the plane $(O_p^{(j)} x_p^{(j)} z_p^{(j)})$, then the equation systems (7) turn into:

$$\begin{aligned} x_p^{(j)} &= \mp[B] \cos \vartheta_a^{(j)}, \\ y_p^{(j)} &= \mp[B] \sin \vartheta_a^{(j)}, \\ z_p^{(j)} &= p_s^{(j)} (\vartheta_a^{(j)} - \pi/2) \pm u^{(j)} \cos \xi^{(j)}, \\ B &= u^{(j)} \sin \xi^{(j)} - p_t^{(j)} (\vartheta_a^{(j)} - \pi/2). \end{aligned} \quad (8)$$

3. Basic Geometric Characteristics of the Conic Convolute Surface

Parameter of Distribution. It is known [6, 11, 12] that the main characteristic of surfaces with rectilinear generatrices is their parameter of the distribution. When surfaces of such type are generated, the rectilinear generatrix passes from its initial position to an infinitely closed vicinal position, rotating at an angle and displacing at some distance. These two quantities are infinitely small, but their ratio has its limits, which is titled a *parameter of the distribution*.

Following Fig. 5 the transition of the rectilinear generatrix $L^{(j)}$, (which is characterized by the parameter ϑ), in a position L' , characterized by infinitely closed value $\vartheta + \Delta\vartheta$, then it rotates to an angle $\Delta\varphi$ and deviates from its initial position to a distance $\Delta\lambda = MM'$. As has been already mentioned, these values are infinitely small, and their ratio tends to a certain limit, which is called a parameter of distribution [12]:

$$h = \lim_{\Delta\vartheta \rightarrow 0} \frac{\Delta\lambda}{\Delta\varphi} \quad (9)$$

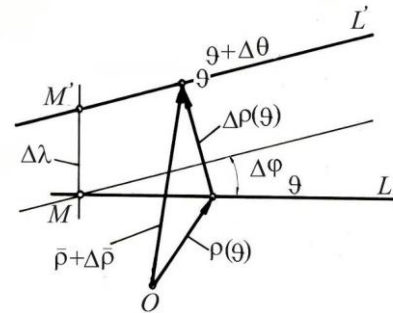


Fig. 5 Transition of the generatrix L into an infinitely close position L'

To determine the distribution parameter $\Sigma^{(j)}$ of the conic convolute helical surface $\Sigma_1^{(j)}$, the vector equation (1) is presented of the type [2]:

$$\vec{\rho}_1^{(j)} = \vec{\rho}_0^{(j)} (\vartheta^{(j)}) + R_0^{(j)} \vec{l}^{(j)}, \quad (10)$$

where $\vec{\rho}_0^{(j)} = \vec{\rho}_0^{(j)} (\vartheta^{(j)}) \{ \chi_1^{(j)}, \chi_2^{(j)}, \chi_3^{(j)} \}$ is an equation of a directed helical line on the directed cylinder $C^{(j)}$; $\chi_1^{(j)}, \chi_2^{(j)}, \chi_3^{(j)}$ - projection of the vector $\vec{\rho}_0^{(j)}$ in the coordinate system $S_p^{(j)}$; $\vec{l}^{(j)} \{ l_1^{(j)}, l_2^{(j)}, l_3^{(j)} \}$ - directed unit vector of the generatrix line $\Sigma^{(j)}$; $l_1^{(j)}, l_2^{(j)}, l_3^{(j)}$ - projections of $\vec{l}^{(j)}$ in the coordinate system $S_p^{(j)}$.

For the case illustrated in Fig. 1, it is written:

$$\begin{aligned}\chi_1^{(j)} &= r_0^{(j)} \cos \vartheta^{(j)}, \quad \chi_2^{(j)} = r_0^{(j)} \sin \vartheta^{(j)}, \\ \chi_3^{(j)} &= p^{(j)} \cdot \vartheta^{(j)}, \\ l_1^{(j)} &= \pm \sin \xi^{(j)} \sin \vartheta^{(j)}, \quad l_2^{(j)} = \mp \sin \xi^{(j)} \cos \vartheta^{(j)}, \\ l_3^{(j)} &= \pm \cos \xi^{(j)},\end{aligned}\quad (11)$$

Then, applying (9), as it is shown in [6, 12], for the studied conic convolute helicoid it can be written:

$$h^{(j)} = \frac{\begin{vmatrix} d\chi_1^{(j)} & l_1^{(j)} & dl_1^{(j)} \\ d\chi_2^{(j)} & l_2^{(j)} & dl_2^{(j)} \\ d\chi_3^{(j)} & l_3^{(j)} & dl_3^{(j)} \end{vmatrix}}{(dl_1^{(j)})^2 + (dl_2^{(j)})^2 + (dl_3^{(j)})^2}. \quad (12)$$

For $\Sigma^{(j)}$ from (12) it is obtained the following:

$$h^{(j)} = p^{(j)} + r_0^{(j)} \cot \xi^{(j)}. \quad (13)$$

Cross section of the conic convolute helicoid

The equation of the illustrated in Fig. 1 conic convolute helicoid surfaces with the plane $O_p^{(j)} x_p^{(j)} y_p^{(j)}$, i.e. when $z_p^{(j)} = 0$, has the following parametric form:

$$\rho_p^{(j)} = \sqrt{(r_0^{(j)})^2 + \left(\frac{p^{(j)} \vartheta^{(j)}}{\cot \xi^{(j)}} \right)^2}. \quad (14)$$

In Cartesian coordinates, the cross-section of the convolute helicoids $\Sigma_I^{(j)}$, when $z_p^{(j)} = C_{z_p}^{(j)} = \text{const.}$, is described with the following system of equations:

$$\begin{aligned}x_p^{(j)} &= r_0^{(j)} \cos \vartheta^{(j)} + C_{z_p}^{(j)} \sin \vartheta^{(j)}, \\ y_p^{(j)} &= r_0^{(j)} \sin \vartheta^{(j)} - C_{z_p}^{(j)} \cos \vartheta^{(j)}, \\ C &= \left[\tan \xi^{(j)} \left(\frac{C_{z_p}^{(j)}}{\vartheta^{(j)}} - p_s^{(j)} \right) \mp p_t^{(j)} \right].\end{aligned}\quad (15)$$

Equations (15) are written in the form:

$$\begin{aligned}x_p^{(j)} &= r_0^{(j)} \cos \vartheta^{(j)} + b^{(j)} \vartheta^{(j)} \sin \vartheta^{(j)}, \\ y_p^{(j)} &= r_0^{(j)} \sin \vartheta^{(j)} - b^{(j)} \vartheta^{(j)} \cos \vartheta^{(j)},\end{aligned}\quad (16)$$

$$\text{where } b^{(j)} = \tan \xi^{(j)} \left(\frac{C_{z_p}^{(j)}}{\vartheta^{(j)}} - p_s^{(j)} \right) \mp p_t^{(j)}.$$

The essence of the cross-section of the conic convolute helicoid can be clarified by introducing circular vector functions [4, 6] $\bar{l}^{(j)} = \bar{l}^{(j)}(\vartheta^{(j)})$ and $\bar{g}^{(j)} = \bar{g}^{(j)}(\vartheta^{(j)})$, for which the condition is fulfilled:

$$\begin{aligned}\bar{l}^{(j)} &= \bar{i}_p^{(j)} \cos \vartheta^{(j)} + \bar{j}_p^{(j)} \sin \vartheta^{(j)}, \\ \bar{g}^{(j)} &= -\bar{i}_p^{(j)} \sin \vartheta^{(j)} + \bar{j}_p^{(j)} \cos \vartheta^{(j)}.\end{aligned}\quad (17)$$

Since $d\bar{l}^{(j)}/d\vartheta^{(j)} = \bar{g}^{(j)}(\vartheta^{(j)})$ then the direction of the vector $\bar{g}^{(j)}(\vartheta^{(j)})$ is determined by the counterclockwise rotation viewed from the positive direction of the axis $O_p^{(j)} z_p^{(j)}$ and it is tangent to the directed circle (determined by the directed cylinder $C^{(j)}$). By using $\bar{r}_p^{(j)} = x_p^{(j)} \bar{i}_p^{(j)} + y_p^{(j)} \bar{j}_p^{(j)}$, for the cross-section of the conic convolute surface $\Sigma_I^{(j)}$ (following equations (16)) it can be written:

$$\bar{r}_p^{(j)} = r_0^{(j)} \bar{l}^{(j)}(\vartheta^{(j)}) - b^{(j)} \vartheta^{(j)} \bar{g}^{(j)}(\vartheta^{(j)}). \quad (18)$$

Let the cross-section of $\Sigma_I^{(j)}$ in the coordinate plane $O_p^{(j)} x_p^{(j)} y_p^{(j)}$ is illustrated, i.e. for the case $C_{z_p}^{(j)} = 0$, when

$$b^{(j)} = -\frac{p^{(j)}}{\cot \xi^{(j)}} > 0.$$

The above condition and the vector equality (18), determine the type of the cross-section of the studied conic convolute helicoids $\Sigma_I^{(j)}$, shown correspondingly in Fig. 6 [11].

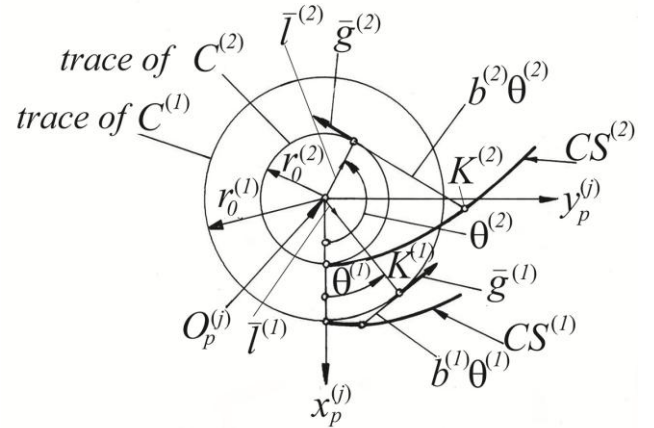


Fig. 6 Cross-section of the conic convolute helicoids $\Sigma_I^{(j)}$ of I type: $CS^{(j)}$ - line of the cross-section of the $\Sigma_I^{(j)}$

Axial section and axial angle of $\Sigma_I^{(j)}$. The equation of the axial section is obtained after the substitution of $y_p^{(j)} = 0$ in (2):

$$\begin{aligned}x_p^{(j)} &= \frac{r_0^{(j)}}{\cos \vartheta^{(j)}} = r_0^{(j)} \sec \vartheta^{(j)}, \\ z_p^{(j)} &= -p^{(j)} \text{conv}(\vartheta^{(j)}, k^{(j)}),\end{aligned}\quad (19)$$

$$\text{where } k^{(j)} = -\frac{r_0^{(j)}}{p^{(j)}} \cdot \cot \xi^{(j)} > 0,$$

$$\text{conv}(\vartheta^{(j)}, k^{(j)}) = k^{(j)} \tan \vartheta^{(j)} - \vartheta^{(j)}.$$

The analytical type (19) of the axial section of the helicoid described by system (2) corresponds to its special geometry of a conic convolute helicoid surface, which is generated according to Fig. 1.

$$\begin{aligned} \frac{dx_p^{(j)}}{d\vartheta^{(j)}} &= r_0^{(j)} \frac{\sin \vartheta^{(j)}}{\cos^2 \vartheta^{(j)}}, \quad \frac{dz_p^{(j)}}{d\vartheta^{(j)}} = -p^{(j)} \frac{k^{(j)} - \cos^2 \vartheta^{(j)}}{\cos^2 \vartheta^{(j)}} \\ \frac{dz_p^{(j)}}{dx_p^{(j)}} &= -\frac{p^{(j)}}{r_0^{(j)}} \frac{k^{(j)} - \cos^2 \vartheta^{(j)}}{\sin \vartheta^{(j)}}, \\ \frac{d^2 z_p^{(j)}}{dx_p^{(j)2}} &= -\frac{p^{(j)}}{(r_0^{(j)})^2} \frac{\cos^3 \vartheta^{(j)} (1 - k^{(j)} + \sin^2 \vartheta^{(j)})}{\sin^3 \vartheta^{(j)}}. \end{aligned} \quad (20)$$

Since the axial section of $\Sigma_1^{(j)}$, in the most common case, is asymmetric, the study is carried out for $\vartheta^{(1)} \in [0, \pi/2)$ and $\vartheta^{(2)} \in (-\pi/2, 0]$.

When $\vartheta^{(j)} = 0$, $x_p^{(j)} = r_0^{(j)}$ and $z_p^{(j)} = 0$, this point corresponds to the peak of the "axial section" curve. When $\vartheta^{(j)}$ varies from 0 to $\pm \pi/2$, $x_p^{(j)}$ grows from $r_0^{(j)}$ to $+\infty$, and $z_p^{(j)}$ changes to $\pm \infty$. Therefore, the graphics of the curves of the axial section (19) have asymptotes of the form:

$$\begin{aligned} z_p^{(j)} &= A^{(j)} x_p^{(j)} + B^{(j)}, \\ A^{(j)} &= \lim_{x_p^{(j)} \rightarrow \infty} \frac{z_p^{(j)}(x_p^{(j)})}{x_p^{(j)}} = \pm \cot \xi^{(j)}, \\ B^{(j)} &= \lim_{x_p^{(j)} \rightarrow \infty} [z_p^{(j)} - A^{(j)} x_p^{(j)}] = \pm p^{(j)} \frac{\pi}{2}. \end{aligned} \quad (21)$$

Then the equations of the asymptotes of the curves, constituting the axial section of $\Sigma_1^{(j)}$ are of the form

$$z_p^{(j)} = \pm \cot \xi^{(j)} x_p^{(j)} \pm p^{(j)} \frac{\pi}{2}, \quad (j=1, 2), \quad (22)$$

and for $j=1$ the upper signs are valid, and for $j=2$ - the lowers ones.

When the angle $\delta^{(j)} = \xi^{(j)} - \pi/2$ is introduced (see Fig. 7 and Fig. 8), then the equation (22) takes the form:

$$z_p^{(j)} = \mp \tan \delta^{(j)} x_p^{(j)} \pm p^{(j)} \cdot \pi/2. \quad (23)$$

The points of intersection of the asymptotes with the coordinate axis $O_p^{(j)} z_p^{(j)}$ are determined from (23). Their applicate (z-axes) are:

$$z_p^{(j)} = \pm p^{(j)} \cdot \pi/2, \quad (24)$$

The points of intersection of the asymptotes with the axis $O_p^{(j)} x_p^{(j)}$ have abscissas defined by equality:

$$x_p^{(j)} = \frac{p^{(j)}}{\tan \delta^{(j)}} \cdot \frac{\pi}{2} = \frac{r_0^{(j)} \pi}{2k^{(j)}}. \quad (25)$$

The inflection points of the curves of the axial section are obtained from the condition

$$\frac{d^2 z_p^{(j)}}{dx_p^{(j)2}} = 0. \quad (26)$$

Considering (20), the condition (26) is satisfied, if $\cos^3 \vartheta^{(j)} (1 - k^{(j)} + \sin^2 \vartheta^{(j)}) = 0$, i.e. when

$$\vartheta^{(j)} = \pm \arcsin \sqrt{k^{(j)} - 1} \quad \left(\vartheta^{(j)} \neq \pm \frac{\pi}{2} \right). \quad (27)$$

If the condition $\vartheta^{(j)} = \pm \pi/2$ is fulfilled, the inflection points of the curves of the axial section go into $\pm \infty$. If condition (27) is satisfied, these points will exist for

$$1 < k^{(j)} < 2. \quad (28)$$

The form of the curves of the axial section of the conic convolute helicoid $\Sigma_1^{(j)}$ is analyzed both for the case defined by condition (28).

Case $k^{(j)} = \pi/2$. According to (27) and (28), in this case, there will be inflection points on the curves of the axial section that corresponds to $\vartheta^{(j)} = \pm \arcsin \sqrt{\pi/2 - 1}$ ($j=1, 2$). It follows from equality (25) that through the vertices of the curves delineating the axial section of $\Sigma_1^{(j)}$, their asymptotes go through. This case of an axial section is illustrated in Fig. 7 [11].

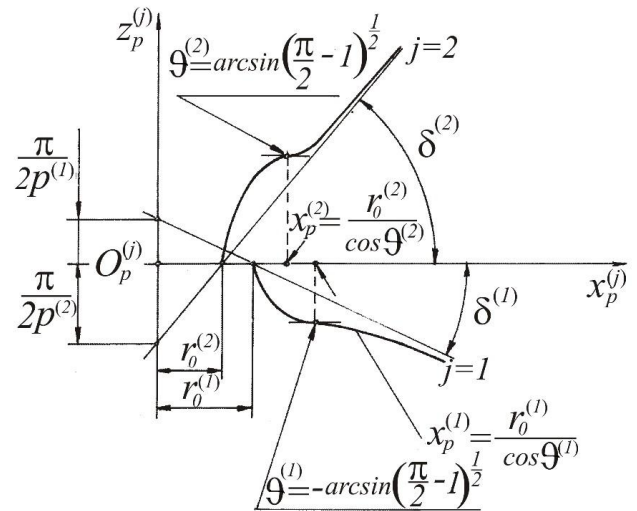


Fig 7 Curves of the axial section of conic convolute helicoids $\Sigma_1^{(j)}$ ($j=1, 2$) when $k^{(j)} = \pi/2$

Case $1 < k^{(j)} < \pi/2$. Applying the above reasoning, it can easily be seen that the curves of the axial section have the form illustrated in Fig. 8.

Each of the theoretical curves of the axial section of the conical convolute helicoid $\Sigma_1^{(j)}$, considered for the entire interval of $\vartheta^{(j)}$ (i.e. when $\vartheta^{(j)} \in [0, \pi/2)$ and $\vartheta^{(j)} \in (-\pi/2, 0]$, ($j=1, 2$)) is symmetrical to the axis $O_p^{(j)} x_p^{(j)}$ and has a nodal point, at $\vartheta^{(j)} = \vartheta_1^{(j)}$, which has the following coordinates:

$$\begin{aligned} x_p^{(j)} &= \frac{r_0^{(j)}}{k^{(j)}} \cdot \frac{\vartheta_1^{(j)}}{\sin \vartheta_1^{(j)}}, \\ z_p^{(j)} &= 0. \end{aligned} \quad (30)$$

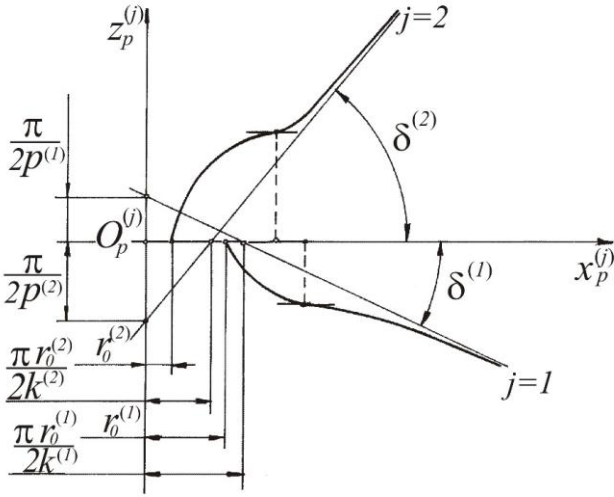


Fig 8. Curves of the axial section of conic convolute helicoids $\Sigma_1^{(j)}$ when $1 < k^{(j)} < \pi/2$

In the considered case, the asymptotes of the axial section $\Sigma_1^{(j)}$, defined by equations (22) and (23), cross the axis $O_p^{(j)}x_p^{(j)}$ at points defined by the expression (25).

From the comparison of (25) and (30), it follows that the abscissas of the points of intersection of the curves of the axial section of the conic convolute helicoid $\Sigma_1^{(j)}$ ($j=1, 2$) with the axes $O_p^{(j)}x_p^{(j)}$ are smaller than those of the points of intersection with the asymptotes with the same axis, due to the fact known from mathematics that

$$1 > \frac{\sin \vartheta^{(j)}}{\vartheta^{(j)}} \geq \frac{2}{\pi}, \quad \text{for } \vartheta^{(j)} \in [-\pi/2, 0] \quad \text{and} \quad \vartheta^{(j)} \in (0, \pi/2].$$

The axial angle $\alpha_s^{(j)}$ in an arbitrary point of the axial section of the studied conic helicoid is obtained from the equations system (20):

$$\tan \alpha_s^{(j)} = \left| \frac{dz_p^{(j)}}{dx_p^{(j)}} \right| = \left| -\frac{p^{(j)}}{r_0^{(j)}} \cdot \frac{k^{(j)} - \cos^2 \vartheta^{(j)}}{\sqrt{1 - \cos^2 \vartheta^{(j)}}} \right|, \quad (31)$$

$$\text{where } k^{(j)} = -\frac{r_0^{(j)}}{p^{(j)}} \cot \xi^{(j)}, \quad \cos \vartheta^{(j)} = \frac{r_0^{(j)}}{x_p^{(j)}},$$

Then

$$\alpha_s^{(j)} = \arctan \left| \frac{p^{(j)} \frac{r_0^{(j)}}{x_p^{(j)}} + x_p^{(j)} \cot \xi^{(j)}}{\sqrt{x_p^{(j)2} - r_0^{(j)2}}} \right|, \quad (32)$$

After substitution of $x_p^{(j)} = r_p^{(j)}$ into (32), it is obtained the axial angle of $\Sigma_1^{(j)}$ in a point in an arbitrary conic surface, coaxial with the outer surface of the conic gear equipped with convolute helical teeth of the studied type.

4. Singular Contact Points on Conic Linear Helicoids

It is known [13, 14] that for the cases prevailing in technological practice when generating cylindrical worms and cylindrical worm cutters, whose tooth surfaces are linear helicoids, knives are used as cutting tools, the cutting edges of which are arranged in a certain way relative to the geometric axis (axis of rotation) of the generated product.

The cutting edges of the knives represent the generatrix lines $\Sigma^{(j)}$ ($j=1, 2$) (Fig. 1) that generate the linear surfaces. This technological approach is also applicable in the practical implementation of conic linear helicoids [2].

Conic convolute helicoid. To prevent the phenomenon of "undercutting" of the active tooth surfaces of gear transmissions and instruments, representing parts of conic linear helicoids, during their generation, it is necessary to define conditions for the appearance of the ordinary points (points of undercutting) on them. As already illustrated, the conic linear helicoids $\Sigma_1^{(j)}$ ($j=1, 2$) (and in particular the conic convolute helical surface) have the form: $\bar{\rho}_1^{(j)} = \bar{\rho}_1^{(j)}(u^{(j)}, \vartheta^{(j)})$.

Then the normal vector $\bar{n}_1^{(j)}$ at $\Sigma_1^{(j)}$ ($j=1, 2$) in an arbitrary point $N^{(j)}$ is defined by

$$\bar{n}_1^{(j)} = \frac{\partial \bar{\rho}_1^{(j)}}{\partial u^{(j)}} \times \frac{\partial \bar{\rho}_1^{(j)}}{\partial \vartheta^{(j)}}, \quad (33)$$

where $\frac{\partial \bar{\rho}_1^{(j)}}{\partial u^{(j)}}$ and $\frac{\partial \bar{\rho}_1^{(j)}}{\partial \vartheta^{(j)}}$ are vectors in point $N_1^{(j)}$ from the conic helical surface $\Sigma_1^{(j)}$, tangent to the coordinate lines $u^{(j)} = \text{constant}$ and $\vartheta^{(j)} = \text{constant}$.

It is known [12], that point $N^{(j)}$ from $\Sigma_1^{(j)}$ is singular (node), if in it a normal vector $\bar{n}_1^{(j)}$ cannot be defined, i.e. the following condition is fulfilled:

$$\bar{n}_1^{(j)} = \bar{0}. \quad (34)$$

Then from (2), for the projections of the normal vector $\bar{n}_1^{(j)}$ in the coordinate system $S_p^{(j)}$ can be written:

$$\begin{aligned} n_{1,x_p}^{(j)} &= \mp h^{(j)} \sin \xi^{(j)} \cos \vartheta^{(j)} - D \cos \xi^{(j)} \sin \vartheta^{(j)}, \\ n_{1,y_p}^{(j)} &= \mp h^{(j)} \sin \xi^{(j)} \sin \vartheta^{(j)} + D \cos \xi^{(j)} \cos \vartheta^{(j)}, \\ n_{1,z_p}^{(j)} &= D \sin \xi^{(j)}. \end{aligned} \quad (35)$$

$$D = (u^{(j)} \sin \xi^{(j)} - p_t^{(j)} \vartheta^{(j)})$$

From (35) it can be seen, that condition (34) is never satisfied for the conic convolute helicoid, since $h^{(j)} \neq 0$. This means that the conic convolute helicoid consists of only non-singular points.

5. Conclusion

Basic analytical and geometrical synthesis of conic convolute helicoids is realized. The obtained equations show a theoretical possibility, depending on the basic geometrical characteristics of the

designed conic convolute worm, to generate the active surfaces of its helical teeth as parts of the intended pairs of conic convolute helicoids. In this study are shown the analytical dependences of the cross-section and the axial section, which are important for the synthesis of the conic helical surfaces. On the base of the realized studies, is created a computer program, for illustrations of these helicoids. The illustrated, in this work, equations of conic helicoids, as well as the analytical descriptions of their cross-sections and axial sections, are important geometric characteristics of the active tooth surfaces of conic worms or conic hobs. They are related to the technological synthesis of gear mechanisms with the application of these new types of helical surfaces operating in the condition of working and/or instrumental meshing. The notes made about the appearance of undercutting cutting points on these surfaces, with the chosen generation approach, are also particularly essential for their technological synthesis.

6. Acknowledgment

This work has been accomplished with the financial support by the Grant No BG05M2OP001-1.002-0011-C02 financed by the Science and Education for Smart Growth Operational Program (2014-2020) and co-financed by the European Union through the European structural and Investment funds.

7. References

1. E. Abadjieva. Spatial Rack Drives. Mathematical Modelling for Synthesis. VDM Verlag Dr. Müller e.K., 2011, 72 pp., (ISBN: 978-3-639-24045-0)
2. V. Abadjiev. Gearing Theory and Technical Applications of Hyperboloid Drives, Sc. D. Thesis, Institute of Mechanics, Bulgarian Academy of Sciences, Sofia, 309, (2007),(in Bulgarian)
3. Abadjieva, E., V. Abadjiev. Regular Mechanical Transformation of Rotations into Translations: Part 2. Kinematic Synthesis of the Elements of High Kinematic Joints, Realizing the Process of Motions Transformations. J. of Theor. and Appl. Mech., Sofia, 47(3), 3-24 (2017)
4. Lashnev, S., Yulikov, M. Calculation and Design of Metal-Cutting Tools with an IBM Application. Mashinostroenie, Moscow, 391, (1975)
5. Litvin, F., Fuentes, A. Gear Geometry and Applied Theory. Second Edition, Cambridge University Press, 800, (2004)
6. Lyukshin, V. The Theory of Helical Surfaces in the Design of Cutting Tools. Mashinostroenie Publishing House, Moscow, 371, (1968)
7. Semchenko, I., Magyushin, M., G. Saharov. Design of Metal Cutting Tools. Mashgiz, Moscow, 952, (1962)
8. Abadjiev, V., Okhotsimsky, D., Platonov, A. Research on the Spatial Gears and Applications, Keldysh Institute of Applied Mathematics, Russian Academy of Sciences, Preprint No 89, Moscow, (1997).
9. BDS 8540-84, 1985. Gear sets. Common terms. Definitions and symbols. Institute of Standardization, Sofia, (1985).
10. Abadjiev, V. Mathematical Modelling for Synthesis of Spatial Gears, Journal of Process Mechanical Engineering., Proc Inst. Mech Engrs, Vol. 216, Part E, pp. 31-46, (2002).
11. Abadjiev V., E. Abadjieva. Conic Linear Helicoids: Part 1. Synthesis and Analysis of the Basic Geometric Characteristics. Gears in Design, Production, and Education. Mechanisms and Machine Science, 101. Springer, Cham, 339-360, (2021)
12. Rashevsky, P. Course of Differential Geometry. Ed. State Publishing House of Technical and Theoretical Literature, Moscow, 1956, 420, (1956).
13. Ginzburg, E., N. Golovanov, N. Firun, N. Halebsky. Gear Transmissions. Mashinostroenie, Leningrad, 416, (1980)
14. Golovanov, N., E. Gizburg, N. Firun Spatial Transmissions, and Worm Gear Mechanisms. Mashinostroenie, Leningrad, 515, (1967).

Design for Sustainability: A Review

Jelena Djokikj, Elisaveta Doncheva

"Ss. Cyril and Methodius" University in Skopje, Faculty of Mechanical Engineering, 1000 Skopje, North Macedonia
jelena.djokikj@mf.edu.mk

Abstract: Sustainability is topic of great concern since the last decade and still today does not lose of its popularity. Reason for that is that the contemporary way of living is causing great damages to the environment. Designers have been talking about changing the ways in which the products are designed in order to have sustainable product. But, for achieving sustainability many aspects need to be addressed, such as: cultural, social, economical and technological. Nowadays, we believe that these aspects are on higher level and we can talk about sustainable design.

Every product development process starts with the design phase and this is why we believe that it is most important for making improvements of the products. In this paper we have the premise that good and appropriate design can have positive influence on the sustainability. In order to check the validity of the premise we are reviewing paper dealing with sustainability, eco design, and engineering materials.

Keywords: DESIGN PROCESS, SUSTAINABILITY, CIRCULAR ECONOMY

1. Introduction

Since the of the time homo sapience's humans depended on the nature, and therefore cared for it and nurture it. However, with the industrialization and globalization humans have been obsessed with satisfying their needs. Satisfying those needs meant cutting down forest, endangering lives of hundreds if not millions species (animals, birds, fish, and plants), causing climate change and what not. Human activity has even been connected to a global "sixth mass extinction" of animal species and "massive anthropogenic erosion of biodiversity and of the ecosystem services essential to civilization" [1].

Over the years many different terms have been in circulation. Earliest are green design and then eco design, referring to ecofriendly design of products, meaning that in the design phase the designer takes care of minimizing the negative effects on the nature throughout the whole lifecycle of the product.

In the later years terms such as sustainable design have emerge, taking into account the whole process including the sociological and economic factors. So it can be said that the sustainability stands for much broader aspects, having the UN'S sustainable goals as reference. The concept of sustainable development stands for harmonizing development processes with respect for the environment, in the interest of future generations. Going by an analogy between the processes of natural transformation and those of industry, sustainability concepts take inspiration from nature's teachings in an attempt to optimize the flows of resources that characterize the entire industrial system and the life cycle of products [2].

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [3]. With this definition of sustainable development, in 1987 the World Commission on Environment and Development (WCED) outlined what is now widely recognized as the guiding objective of the current process of economic and technological development - to ensure that the use of environmental resources to satisfy present demands are managed in such a way that they are not left so damaged or impoverished that they cannot be used by future generations. After more than 30 years since the publication, it now seems that a complete vision of the problem has finally matured, where sustainable development is considered a process that includes all three key factors: **economic, sociocultural and environmental** [4]. It is important to stress that the science and the technology are in direct connection to every one of the key factors and are expected to provide data and tools for achieving balance [5] which is the necessary for sustainable development.

In order produce eco products or products that are ecofriendly the industry has to adapt as well. This is the beginning of industrial ecology (IE) which has to provide better understanding and application of the system necessary for achieving sustainability [6]. According to scholars [7; 8; 9] working in this discipline in order to

obtain sustainability the industrial ecosystem must be closed cycle same as the biological ecosystems. In the recent years the term circular design has been in use, the term which clearly stands for achieving a closed loop of the product's life cycle. Throughout the years the IE slowly transitioned into circular economy (CE). The field of IE provided the foundations for the idea of a CE [10; 11; 12]. Building on original IE thinking [13; 14; 15] the CE has recently been (re-)popularized as both a public policy and business concept [16; 17]. Developed countries [18; 19; 20] are trying to adopt CE principles as guidelines for the envisioned redesign of their economies [12], which requires changes on the macro-level (cities, provinces, regions, and nations), meso-level (networks, eco-industrial parks), and micro-level (individual companies, consumers) [11].

We believe that the design has crucial role in achieving sustainable development or CE. In this paper, we are reviewing different sources on eco design, sustainability and circular economy in order to comprehend the influence that the design process has in each of these disciplines.

2. State of the art

Eco design can be considered as a part of the sustainable product design. It is a well-known discipline that provides designers with design methodologies, eco design strategies, methods and principles helping them and guiding them into the design process of or creating products that do not have large negative implication on the environment throughout the whole life cycle [21; 22; 23; 24; 25]. But the countries and so the companies are slowly shifting towards the circular economy (CE), which requires different approach when designing. Designers are lacking methodologies and strategies to guide them through circular product design when designing for the circular economy [26]. den Hollander and colleagues [27] in their research focus on creating methodology for circular product design, focusing of product integrity, which they believe is the key to no waste policy of the CE. The authors' propose a typology of three stages for product integrity: long use, extended use and recovery. Design approaches for long use are method of resisting the obsolescence, which encompasses: design for physical durability and design for emotional durability [28]. Design approaches for extended use are in fact postponing obsolescence and those are design for maintenance and design for upgrading. Design approaches for recovery are: design for decontextualizing, design for repair, design for refurbishment, and design for remanufacture, aimed at reversing the obsolescence [27].

Emotional durability researched by Page [28] is something that is rarely being discussed and researched. But that is not because it is not important but because is complex area requiring large subject sample in order to make objective conclusion. She conducts a literature review from which can be concluded that emotional durability and product attachment are influenced by different

factors. These factors can be used by the designer in order to design products that are more desirable and harder to toss away.

CE is slowly becoming something that the societies are striving upon, and the main goal of the CE is zero waste. This is why many researchers work on proposing different strategies and methodology that provide no waste.

The CE may be defined as "a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, and repair, reuse, remanufacturing, refurbishing, and recycling" [29].

In this age of extensive consumeristic human behavior, massive amount of waste are produced every day. One area of high number of waste is the garment industry, since the production is high and at the same time the styles are changing very fast. Achieving zero waste in the industry requires major changes in the production processes which is long and expensive task. No waste would mean that there should be 100% resource use in the production. Along with the changes in the production process, also there should be changes in the aesthetic/fit of the contemporary designs [30]. As their contribution to the CE, Kääriäinen and Niinimäki [31] conduct material research in order to create sustainable textile materials. The empirical basis of this study consists of five material research and development projects. They investigate the projects to understand not only the approaches to producing sustainable textile materials, but also to map the differences in the scientific dialogues.

On the other hand numerous authors critique the waste hierarchy. Behrens and colleagues [32] critique it for having a positive impact on dematerialization and decoupling, given that it focuses only on waste and does not address material inputs directly, nor consider economic output. Van Ewijk and Stegemann [33], provides a critique relating to the hierarchy's priority orders. First, they argue, inclusion of an option in a priority order legitimizes its existence (i.e., disposal). Second, the common understanding is that one needs to move up the hierarchy rather than necessarily achieve the highest outcome. It is about the direction of change rather than the end goal, which illustrates the relative nature of the waste hierarchy. McDonough and Braungart [34] refer to the waste hierarchy as the logic of death and argued that solution should be made to design for abundance. Their argument is that growth isn't in and of itself wrong, only the way we do it and that the things society and industry tends to want to grow like product sales and dividends – unless also tethered to the finite environmental (and social) limits of our planet – are the very things that can make abundance for all impossible to achieve.

3. Discussion

Authors of the review paper have different proposals for achieving sustainability and CE. The difference is that in the sustainable development the goal is to prevent occurrence of waste or to minimize it, where as in the CE there should not be waste. This main difference is the reason for different approaches and proposed methodologies. In the prevention of waste we must think in the design process on how to design products that do not use abundance of natural resources that do not require long and complex production processes, localised manufacturing, optimised transport, fast assembly and possibility for reuse, remanufacture od recycle. In the CE there should not be waste this is why there are just two approaches:

- Design for extending the useful life of a product and
- Design for recycling.

In Design for extending the useful life of a product are approaches for long use (design for durability and design for emotional durability), approaches for extended use (design for maintenance, design for upgrading) and approaches for recovery

(design for decontextualizing, design for repair, design for refurbishment, design for remanufacture) [27].

Extended life cycle – ref

The ultimate goal of *design for product integrity* is to minimize and ideally eliminate environmental costs by preserving or restoring the product's added economic value over time. Extended product lifetimes, however, do not always result in a net reduction of environmental load. Over time, newer versions of products may be developed that incorporate more efficient technologies. From that moment on, the environmental impacts that arise from the prolonged use of a product may become larger than the embedded impacts of a more efficient replacement product [35]. Because the Inertia Principle does not account for this, product designers need to understand the ecological consequences of their design interventions.

Design for recycling consists approaches and strategies for waste management and transform it into resources. In order to ensure that, in the design process the appropriate type and amount of material should be selected. The selected material need to be recyclable, but also there should be market demand for it and the recycling process needs to be efficient and economical.

4. Conclusion

Sustainability and CE are important topics for the contemporary society and it is a positive thing that they attract so many researchers.

In this paper we analyzed different research papers with different approaches in the sustainability and CE. But every one of the implied that design phase is the crucial for achieving the goal, whether it is extended life, recyclability or zero waste. This only affirms the premise from the beginning of the paper that the designer is the one that needs to design product that can have extended life or be recycled.

For further research the number of researched paper has to be extended and their categorization according to the specific area of interest should be made.

References

1. Ceballos, Gerardo, Paul R. Ehrlich, and Rodolfo Dirzo. (2017). Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines. *Proceedings of the national academy of sciences* 114.30.
2. Giudice, F., La Rosa, G., & Risitano, A. (2006). *Product design for the environment: a life cycle approach*. CRC press.
3. Holden, E., Linnerud, K., & Banister, D. (2014). Sustainable development: Our common future revisited. *Global environmental change*, 26, 130-139.
4. Robèrt, K. H., Schmidt-Bleek, B., De Lardere, J. A., Basile, G., Jansen, J. L., Kuehr, R., ... & Wackernagel, M. (2002). Strategic sustainable development—selection, design and synergies of applied tools. *J. Clean. Prod.*, 10(3), 197-214.
5. Munasinghe, M. (2001). Sustainable development and climate change: applying the sustainomics transdisciplinary meta-framework. *I. J. G. Env. I*, 1(1), 13-55.
6. Korhonen, J. (2004). Industrial ecology in the strategic sustainable development model: strategic applications of industrial ecology. *J. Clean. Prod.*, 12(8-10), 809-823.
7. Ayres, R. U. (1989). Industrial metabolism. *Technology and environment*, 23-49.
8. Allenby, B. R. (1992). Achieving sustainable development through industrial ecology. *International Environmental Affairs*, 4(1), 56-68.
9. Jelinski, L. W., Graedel, T. E., Laudise, R. A., McCall, D. W., & Patel, C. K. (1992). Industrial ecology: concepts and approaches. *Proceedings of the National Academy of Sciences*, 89(3), 793-797.

10. Bocken, N. M., Olivetti, E. A., Cullen, J. M., Potting, J., & Lifset, R. (2017). Taking the circularity to the next level: a special issue on the circular economy. *J. Ind. Ecol.*, **21**(3), 476-482.
11. Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *J. Clean. Prod.*, **114**, 11-32.
12. McDowall, W., Geng, Y., Huang, B., Barteková, E., Bleischwitz, R., Türkeli, S., ... & Doménech, T. (2017). Circular economy policies in China and Europe. *J. Ind. Ecol.*, **21**(3), 651-661.
13. Ayres, R., & Ayres, L. (1996). Industrial ecology: towards closing the materials cycle. In *Industrial Ecology*. Edward Elgar Publishing.
14. Ehrenfeld, J. (2004). Industrial ecology: a new field or only a metaphor?. *J. Clean. Prod.*, **12**(8-10), 825-831.
15. Lifset, R., & Graedel, T. E. (2002). Industrial ecology: goals and definitions. In *A handbook of industrial ecology*. Edward Elgar Publishing.
16. Ellen MacArthur Foundation. (2012). *Towards the circular economy*. Ellen MacArthur Foundation.
17. European Commission. 2014. *Moving towards a circular economy*. <http://ec.europa.eu/environment/circular-economy/>. Accessed October 2015.
18. Tong, X., Tao, D., & Lifset, R. (2018). Varieties of business models for post-consumer recycling in China. *J. Clean. Prod.*, **170**, 665-673.
19. Yuan, Z., Bi, J., & Moriguchi, Y. Yuan, (2006). The circular economy: a new development strategy in China. *J. Ind. Ecol.*, **10**.
20. Andersen, M. S. 2007. An introductory note on the environmental economics of the circular economy. *Sustain. Sci.*, **2**(1): 133-140.
21. Pigosso, D. C. A., McAloone, T. C., & Rozenfeld, H. (2015). Characterization of the state-of-the-art and identification of main trends for Ecodesign Tools and Methods: Classifying three decades of research and implementation. *J Indian Inst Sci*, **95**(4), 405-428.
22. Bovea, M. D., & Pérez-Belis, V. (2012). A taxonomy of ecodesign tools for integrating environmental requirements into the product design process. *J. Clean. Prod.*, **20**(1), 61-71.
23. EC (European Commission). 2009. Directive 2009/125/EC of the European Parliaments and the Council of 21 October 2009 Establishing a Framework for the Setting of Ecodesign Requirements for Energy-related Products (Recast). (2011). Brussels, Belgium: European Commission Energy.
24. Luttrupp, C., & Lagerstedt, J. (2006). EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development. *J. Clean. Prod.*, **14**(15-16), 1396-1408.
25. Tischner, U., & Deutschland, U. (2000). *How to do EcoDesign?: a guide for environmentally and economically sound design*. Verlag form Praxis.
26. Den Hollander, M. (2018). *Managing Obsolescence: Extending Product Lifetimes in a Circular Economy* (Doctoral dissertation, TU Delft).
27. Den Hollander, M. C., Bakker, C. A., & Hultink, E. J. (2017). Product design in a circular economy: Development of a typology of key concepts and terms. *J. Ind. Ecol.*, **21**(3), 517-525.
28. Page, T. (2014). Product attachment and replacement: implications for sustainable design. *IJSDes*, **2**(3), 265-282.
29. Geissdoerfer, M., Savaget, P., Bocken, N. M., & Hultink, E. J. (2017). The Circular Economy—A new sustainability paradigm?. *J. Clean. Prod.*, **143**, 757-768.
30. McQuillan, H. (2019). Waste, so What? A reflection on waste and the role of designers in a circular economy. *Nordes*, (8).
31. Kääriäinen, P., & Niinimäki, K. (2019). Towards Sustainable Textile Materials: Potential pathways and dialogues between disciplines. *Nordes*, (8).
32. Behrens, A., Giljum, S., Kovanda, J., & Niza, S. (2007). The material basis of the global economy: Worldwide patterns of natural resource extraction and their implications for sustainable resource use policies. *Ecol. Econ.*, **64**(2), 444-453.
33. Van Ewijk, S., & Stegemann, J. A. (2016). Limitations of the waste hierarchy for achieving absolute reductions in material throughput. *J. Clean. Prod.*, **132**, 122-128.
34. McDonough, W., & Braungart, M. (2010). *Cradle to cradle: Remaking the way we make things*. North point press.
35. Bakker, C., Wang, F., Huisman, J., & Den Hollander, M. (2014). Products that go round: exploring product life extension through design. *J. Clean. Prod.*, **69**, 10-16.

Eco-inspired synthesis and photocatalytic application of novel ZnO nanoparticles from peel extract of banana

Daniela Šojić Merkulov*, Sabolč Bogнар, Nina Finčur, Dušica Jovanović
University of Novi Sad Faculty of Sciences, Department of Chemistry, Biochemistry and Environmental Protection,
Trg Dositeja Obradovića 3, 21000 Novi Sad, Serbia
daniela.sojic@dh.uns.ac.rs

Abstract: The time being, one of the greatest concerns is the environmental pollution. Nowadays, various dangerous compounds reach to the air, soil and water. Pharmaceuticals, such as 17 α -ethinylestradiol (EE2), are one of the most emerging pollutants in water ecosystems. Hence, powerful but green approaches should be developed in order to completely remove the pollutants. Heterogeneous photocatalysis is a sustainable and efficient process in the removal of organic pollutants, such as pharmaceuticals. ZnO is one of the most commonly used semiconductors but also possess some drawbacks. In this study novel synthesis pathway of ZnO nanoparticles from banana peel extract was obtained. Besides, the photocatalytic efficiency of the newly synthesized ZnO was examined in the degradation of EE2. Both the eco-friendly ZnO nanoparticles, as well as pure banana peel extract showed a promising photocatalytic activity in the degradation of EE2 under simulated solar irradiation (SSI). Namely, EE2 was completely degraded after 60 min of SSI.

Keywords: ENVIRONMENTAL POLLUTION, SUSTAINABLE WASTEWATER TREATMENT, ADVANCED OXIDATION PROCESSES, HETEROGENEOUS PHOTOCATALYSIS, GREEN SYNTHESIS, ZNO NANOPARTICLES, BANANA PEEL EXTRACT.

1. Introduction

Nowadays, various dangerous compounds reach to the air, soil and water. Environmental pollution is an emerging global issue, with severe impact on natural fields. The water contamination is the second most serious problem, right after the air pollution [1]. Even though all natural ecosystems are exposed to the harmful effects of different pollutants, the water pollution is the most emerging one. Each year, about 380 billion m³ of wastewater is released to the aquatic environment and this amount is expected to be increased by 24% until 2030 [2].

Pharmaceuticals, such as 17 α -ethinylestradiol (EE2), are one of the most emerging pollutants in water ecosystems. EE2 is a synthetic steroid estrogen and commonly applied in controlling ovulation, as well as in treating alopecia, prostate and breast cancer in humans and reproductive disorders. Furthermore, it is also applied in contraceptives and in hormone replacement therapy. Even though this compound can be successfully used for different medical purposes, the human organism cannot it completely use and it can be excreted in the biologically inactive formulation, such as sulfate and glucuronide conjugates, but also as free active molecules. EE2 belongs to the group of endocrine disruptors and has been globally detected at concentrations ranging from 0.3 to 84.0 ng/L in surface water, sanitary sewage, and drinking water and wastewater effluents from sewage treatment plants. Unfortunately, even at low concentrations EE2 can cause serious damages to the living organisms. Several destructive wildlife and human diseases are believed to be caused by EE2. For instance, fish feminization, turtle egg production alterations, functional digestive gland alterations in mussels and also prostate cancer and decreased sperm production in human males [3,4].

Another serious issue is the ineffectiveness of the most commonly used conventional wastewater treatment techniques, which also use harmful chemicals. Hence, powerful but green approaches should be developed in order to completely remove the pollutants.

Advanced oxidation processes (AOPs) are considered to be adequate alternatives. Heterogeneous photocatalysis, as one of the AOPs, is a sustainable and efficient process in the removal of organic pollutants, such as pharmaceuticals [5]. This technique is based on the interaction between semiconductors as photocatalysts and sunlight. As a result, reactive oxygen species are generated, which attack and mineralize the present pollutants. ZnO is one of the most commonly used semiconductors but also possess some drawbacks, which limit its application in photocatalysis. Thus, various ZnO nanoparticles are being synthesized with unique characteristics [6].

The aim of this study was to prepare novel green ZnO nanoparticles from banana peel extract. In addition, the photocatalytic efficiency of the newly synthesized ZnO and pure banana peel extract was examined in the degradation of EE2 under simulated solar irradiation (SSI).

2. Materials and methods

The aqueous solution of EE2 (0.05 mM) was prepared by dissolving appropriate mass in ultrapure water. The solution was stored in dark environment (protected from light) at room temperature.

The synthesis of the novel-green ZnO nanoparticles (ZnO NPs) was conducted using banana-peel-based extract. Banana was obtained from local stores.

Firstly, prior to the ZnO synthesis, the banana peel was washed several times with tap, distilled and ultrapure water. After that, 220 g of washed peel was mixed with 400 mL ultrapure water. The mixture was heated until boiling and cooked for 10 min. Finally, 100 mL of pure extract was separated and stored in a refrigerator for further analyses.

In the eco-friendly synthesis of novel ZnO NPs, ZnSO₄ × 7H₂O (Sigma-Aldrich, St. Louis, MO, USA) was used as a precursor. To begin with, 300 mL banana peel extract was mixed with 1500 mL ZnSO₄ (0.08 M) solution. Then, the pH was set to 10, using 3 M NaOH. During the addition of NaOH, snow-white precipitation was observed, which is proved the formation of ZnO nanoparticles. The mixture was filtrated through a Büchner funnel and the precipitation was collected on a filter paper. The newly-formed ZnO NPs were washed (two times) with ultrapure H₂O, until pH 7. Finally, ZnO nanoparticles were dried in an oven at 100 °C, until constant mass.

3. Analytical procedures

The photodegradation experiments were performed in a photoreactor (TOPT-V, Toption, China). The samples were prepared and irradiated in a photochemical cell made of quartz glass (total volume of ca. 100 mL). The photochemical cells were placed in a circle around the Xe lamp, which was used as simulated solar irradiation. The cells were equally exposed to the irradiation source. Xenon lamp was in a quartz cold trap, which was equipped with water-circulating jackets and connected to a cooler in order to ensure a constant temperature inside the photoreactor (Fig. 1).

The samples of EE2, taken after different times of irradiation using simulated solar irradiation, were firstly filtered through Millipore (Millex-GV, Burlington, MA, USA, 0.22 μ m) membrane filter to remove all possible impurities. After that, they were analyzed using high-pressure liquid chromatograph with fluorescence detector (UFLC-FL, Shimadzu Nexera, Tokyo, Japan)

(excitation and emission wavelength of EE2 were 220 nm and 310 nm, respectively) equipped with Inertsil® ODS-4 column (2.1 mm × 50 mm i.d., particle size 2 µm, 30 °C) was used. Prepared samples (10 µL) were injected and analyzed. The mobile phase (flow rate 0.7 mL/min) was a mixture of acetonitrile and water (80:20, v/v, pH 2.56), while the water was acidified with phosphoric acid, so that the mass fraction of phosphoric acid was 0.1%.

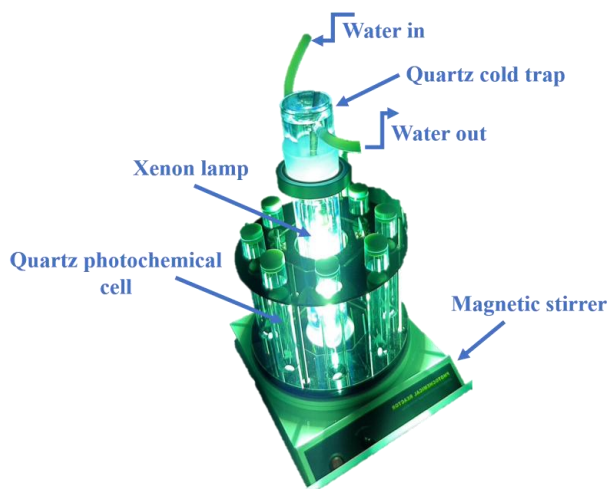


Fig. 1. TOPT-V photoreactor

4. Results and discussion

In order to determine the photocatalytic activity of newly synthesized plant-based ZnO nanoparticles, the photocatalytic degradation efficiency of EE2 was investigated. Firstly, experiments were carried out in the presence of both commercially available ZnO and novel green ZnO NPs. Based on the obtained results (Fig. 2) it can be concluded that banana-peel-based ZnO showed higher photocatalytic activity, since 95% of EE2 was degraded after 60 min of simulated solar irradiation. On the other hand, in the system with commercial ZnO 91% of EE2 was removed, respectively.

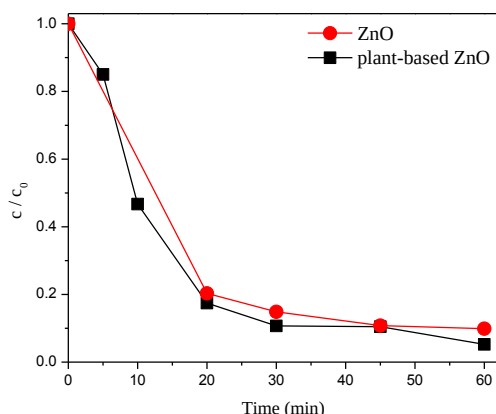


Fig. 2. Kinetics of EE2 (0.05 mM) degradation in the presence of commercial and plan-based ZnO ($\gamma = 1.0$ mg/mL), under simulated solar irradiation

Considering that the novel green ZnO NPs showed the highest removal efficiency, they were used in further experiments. Moreover, the efficiency of pure banana peel extract in the photodegradation of EE2 was also examined. According to the obtained data (Fig. 3), it can be seen that the removal of EE2 was slightly improved in the presence of banana peel extract, compared to the system with ZnO NPs. Namely, 98% of EE2 was successfully degraded in the presence of banana extract, after 60 min of solar irradiation.

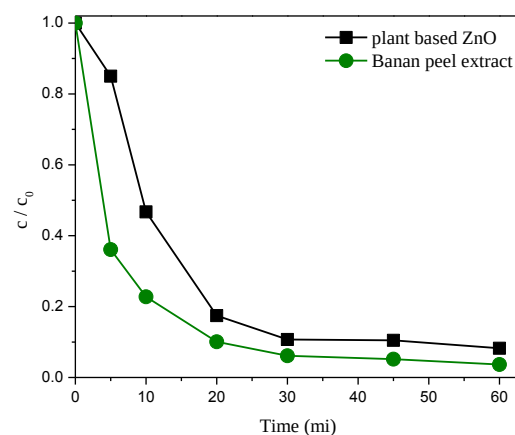


Fig. 3. Kinetics of EE2 (0.05 mM) degradation in the presence of plan-based ZnO ($\gamma = 1.0$ mg/mL) and pure banana extract (5%, v/v), under simulated solar irradiation

5. Conclusion and outlooks

Banana-peel-based ZnO nanoparticles were successfully synthesized via precipitation method with $\text{ZnSO}_4 \times 7\text{H}_2\text{O}$ as a precursor.

Based on the conducted experiments on the photodegradation of EE2, we successfully proved the possible water remediation application of the newly synthesized ZnO-based nanomaterials, as well as banana peel extract.

In general, the phytochemicals present in natural extracts act as reducing and capping agents, thus the synthesis procedure can be accomplished without using the expensive toxic organic stabilizers and complicated time-consuming procedures. Moreover, the plant extracts used for the sustainable synthesis can additionally improve the photocatalytic activity, because of the biomolecules and other natural compounds present in them. However, the exact effects of the biomolecules obtained from plants in the synthesis of nanoparticles, as well as in the photocatalytic processes, are not exactly known and require further investigation.

6. Acknowledgement

The authors acknowledge the financial support of the Science Fund of the Republic of Serbia (Grant No 7747845, *In situ* pollutants removal from waters by sustainable green nanotechnologies-CleanNanoCatalyze).

7. References

1. P. O. Ukaogo, U. Ewuzie, C. V. Onwuka, Environmental pollution: causes, effects, and the remedies, in: P. Chowdhary, A. Raj, D. Verma, Y. Akhter (Eds.), *Microorganisms for Sustainable Environment and Health*, Elsevier Inc., 2020, pp. 419–429.
2. UNESCO, UN-Water, 2020: United Nations World Water Development Report 2020: Water and Climate Change, Paris, UNESCO.
3. D. Ren, F. Chen, Z. Ren, Y. Wang, *Process Saf. Environ. Prot.* **121** (2019), 367–373.
4. F. P. Chaves, G. Gomes, A. Della-Flora, A. Dallegrave, C. Sirtori, E. M. Saggiaro, D.M. Bila, *Sci. Total Environ.* **746** (2020), Art. No. 141041.
5. A. Santos, S. Rodríguez, F. Pardo, A. Romero, *Sci. Total Environ.* **563–564** (2016), 657–663.
6. S. Bognár, P. Putnik, D. Šojić Merkulov, *Nanomaterials* **12** (2022), Art. No. 263.

Effect of solanine on corrosion of steel 3 in lactic acid

Tamara Pyzhik¹, Tatyana Povshok¹, Valery Sarokin¹, Angel Velikov²

Yanka Kupala Grodno State University¹ – Grodno, Belarus, Bulgarian Academy of Sciences, Institute of Metal Science, Equipment and Technologies with Center for Hydro- and Aerodynamics "Acad. A. Balevski", Bulgaria²,
E-mail: pyzhik_tn@grsu.by, povshok_to@grsu.by, sorvg@grsu.by, anmabg@abv.bg

Abstract: The object of research – the natural glycoalkaloid solanine as a possible inhibitor of acid corrosion of steel St3. Modern data on the structure and physico-chemical properties of solanine, such as amphiphilicity, surface activity, basicity, characteristic of modern organic corrosion inhibitors, are presented. The basic concepts are defined: basic nitrogen, solanine amphiphilicity, mass and volume corrosion indicators, corrosion inhibitor, degree of protection, corrosion inhibition coefficient. The literature data on the corrosive activity of lactic acid (MC) are presented and characterized.

KEYWORDS: CORROSION, ST 3, CORROSION INHIBITOR, LACTIC ACID, SOLANINE DEGREE OF PROTECTION, BRAKING COEFFICIENT

1. Introduction

Structural carbon steel St3 of ordinary quality is a universal alloy used in all areas of industry. Various metal structures are made of it, working under normal conditions. However, in an aggressive environment, this steel needs anti-corrosion protection.

One of the modern strategies aimed at combating corrosion is the search for non-trivial corrosion inhibitors based on the principles of Green Chemistry. The starting material for the production of such substances can be not only affordable and renewable plant raw materials, but also industrial waste of plant and animal origin. Rational use of waste, prevention of its adverse or harmful effects on people and the environment, is the most important concept of modern production.

This is especially important for chemical industries associated with the use of aggressive media, or the production of substances that have high corrosive activity. Such substances include oil, solutions of inorganic acids (sulfuric, hydrochloric, orthophosphoric), some salt solutions and solutions of organic acids (formic, acetic, lactic). Numerous studies in recent years have mainly focused on the creation of corrosion inhibitors for strongly acidic media, such as solutions of hydrochloric, sulfuric, nitric acids [1]. The effect of organic acids on the corrosion of industrial steel has not been sufficiently studied.

Of undoubted interest is the study of the corrosive activity of lactic acid (MK). This is due to the constantly increasing demand for this product. MK is widely used in the food industry in the production of beverages, flour products, fruit and vegetable processing. The chemical industry uses MK for the production of neutralizers, for the production of optically active substances, complexing agents and cosmetic products. It is also used as an anti-scale agent, as part of solvents and cleaning agents. Large volumes of MC are used for the synthesis of the biodegradable polymer polylactate (PLA) [2].

According to [3], the global production of MK in 2015 amounted to 354 thousand tons. Currently, the global production capacity is 430 thousand tons. According to the results of 2016, the global demand for MK amounted to 1 million 220 thousand tons and should grow by 16.2% by 2025. Today, the following trends are observed in the global lactic acid market:

- growth of production capacities for the production of MK;
- increase in the share of MK use in non-food industries;
- orientation of the largest manufacturers to the output (PLA).

Further development of the PLA market is predicted, an increase in the production of pharmaceuticals, environmentally friendly food products and food additives.

MK is not produced on an industrial scale in the Republic of Belarus. It has to be purchased abroad. Our country's demand for it has reached 600 tons per year.

An essential condition for increasing the efficiency of enterprises for the production and processing of MK is to increase the reliability of equipment. Anticorrosive protection of equipment, ensuring the safety of the stock of metal products are a guarantee of increasing the safety of production.

Currently, there is fragmentary and contradictory information about the rate of corrosion of metals under the influence of MK. According to [4] stainless titanium-containing high-strength

austenitic steels of the AISI 304 (V2A) and AISI 316Ti (V4A) grades have "excellent" chemical resistance in MK solutions. Other authors note that MK causes corrosion of steel [5]. Yu.I. Batsko and R.S. Reshetova point to the significant role of MK in the corrosion destruction of equipment of sugar factories [6]. Along with the information that MK causes corrosion of steels only at high concentrations [7], there are statements of the opposite nature [8]. Thus, fragmentary and contradictory information about the rate of corrosion of steel under the influence of MK complicates the problem of finding effective corrosion inhibitors.

The aim of the study was to study the dynamics of corrosion of steel St3 in aqueous solutions of various concentrations of MK under the influence of solanine extract.

2. Materials and methods of research

Lactic acid (2-hydroxypropane) has two optical isomers (D and L). It is most often used as a racemate, an optically inactive mixture consisting of equal amounts of D- and L-enantiomers (Figure 1).

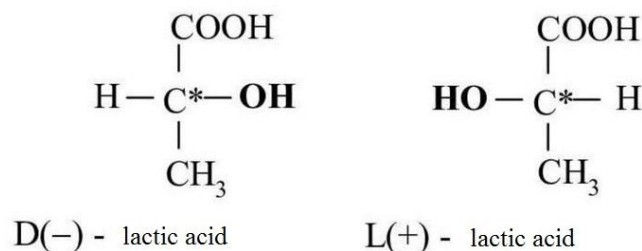


Figure 1 Lactic acid – D- and L-enantiomers

MK is a heterofunctional compound that simultaneously possesses the properties of alcohols and carboxylic acids. This largely explains its high reactivity. Intramolecular hydrogen bonds between hydroxyl and carboxyl groups enhance the acidity of lactic acid (pKa 3,8). It is 80 times stronger than acetic acid.

High hygroscopicity and pronounced acidity are extremely important properties for the manifestation of corrosion activity of MK.

Solanine (Figure 2) is a glycoalkaloid from the Solanaceae family, consisting of aglycone and solatriose. Aglicon is represented by the steroid alkaloid solanidine. The presence of a nitrogen atom in the composition of solanidine gives the whole compound the properties of an organic NH-base with high chemical activity. The carbohydrate fragment of the solatriose molecule includes residues of glucose, galactose and rhamnose monosaccharides. The hydrophobic aglycone and hydrophilic carbohydrate component give the compound an amphiphilic character and determine the surface activity of solanine.

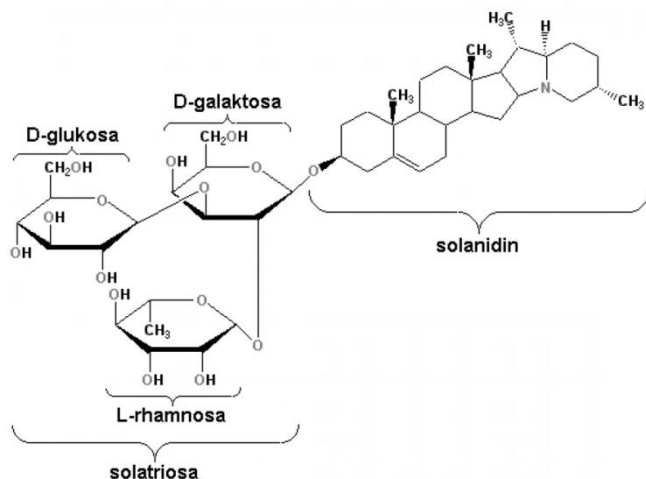


Figure 2 Chemical structure of corned beef

Solanine is a natural alkaloid, it is synthesized in all parts of plants of the Solanaceae family. The highest content of solanine is observed in unripe berries of black nightshade (*Solanum nigrum*). The tubers of ripe potatoes contain a small amount of solanine – about 0.01%. In sprouted, green tubers, the level of solanine increases many times, reaching 0.5%, while especially a lot of solanine appears in potato sprouts and peel [9].

To obtain the solanine extract, potatoes previously aged in sunlight for 30 days were used. A thin layer of peel was removed from the sprouted and green tubers together with the seedlings, crushed and homogenized. Solanine was extracted with a hot ethanol solution acidified with acetic acid. An extract containing a suspension of solanine was used in the experiment.

In laboratory studies, samples of St3 steel weighing 8.07 – 8.23 g, with a diameter of 30 mm were used. A 1M H₂SO₄ solution was used to etch the samples. Then the samples were cleaned with sandpaper, degreased, washed under running water, dried, weighed.

In all variants of the experiments, MK with concentrations of 0.5% (0.055 mol/l); 5% (0.56 mol/l); 50% (6.7 mol/l) were used. The volumes of the reaction mixture with steel samples were adjusted to 80 cm³. The experiments were carried out at a temperature of 200C. In the first series of experiments, 4 cm³ solanine extract was added to lactic acid solutions (4 mg in terms of pure substance) (experiment 1). In the second series of experiments, a suspension of solanine was applied directly to heated steel samples and dried. After applying the extract, the samples were covered with a film. Then the samples were placed in lactic acid solutions without adding solanine to them (experiment 2). Control samples were placed in MK solutions with concentrations of 0.5%, 5% and 50%. Considering that under experimental conditions, electrochemical corrosion of steel St3 proceeds with hydrogen depolarization, the corrosion rate was determined by the volumetric method, fixing the volume of hydrogen released. To do this, the prepared samples were placed in eudiometer flasks, tightly closed and the volumes of hydrogen released were monitored for 24 hours.

The volumetric corrosion index was expressed in cm³/m2h; the mass index was expressed in g/m2h.

To assess the effectiveness of the inhibitor, the degree of protection Z (%) and the inhibitory coefficient γ (inhibitory effect) were determined according to the formula 1 and 2, respectively:

$$\text{Degree of protection: } Z = (K_1 - K_2) / K_1 100\% \quad (1)$$

$$\text{Inhibitory effect: } \gamma = K_1 / K_2 \quad (2)$$

3. Results and discussion

As can be seen from the presented data (Table 1), in the experimental conditions there was no clear relationship between the concentration of MC and the volume of hydrogen released. Thus, in the region of low concentrations of MK, in the range from 0.5% to 5%, an increase in the volume of hydrogen released by 175% was

observed. However, during the transition from a low concentration of 5% to a high concentration of 50%, only a slight (by 14%) increase in the level of hydrogen was recorded. Thus, low concentrations of MK have a more effective effect on the speed of the cathode process than high concentrations.

Table 1: Volumes of released hydrogen, V(H₂), cm³

MK concentration	control	experience 1	experience 2
0,5%	5,2	1,8	1,7
5%	9,1	2,8	2,0
50%	10,4	4,6	5,5

The addition of solanine extract to the reaction mixture led to an effective reduction in hydrogen release at all the studied concentrations of MK – by 2.9, 3.25 and 2.2 times by 0.5%, 5% and 50%, respectively (experiment 1). Identical dynamics of hydrogen release was revealed when solanine was applied directly to the samples (experiment 2), which confirms the effect of inhibition of the corrosion activity of MK by solanine obtained in experiment 1 (Figure 3).

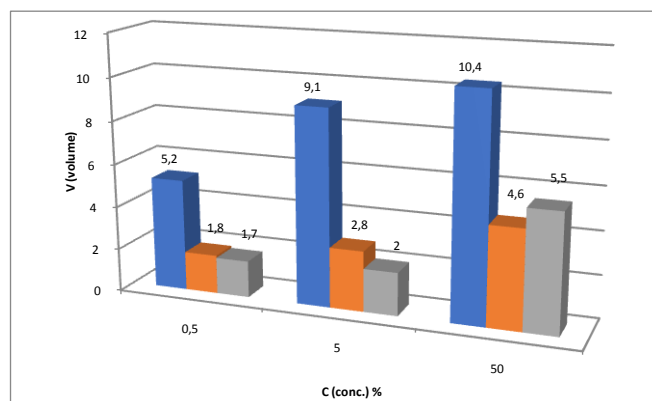


Figure 3 Volumes of released hydrogen, V(H₂), cm³

Data on the corrosion rate obtained by calculating the volume and mass indicators also indicate the activation of the corrosion process with an increase in acid concentration (Table 2). However, this dependence is complex. In the area of low concentrations, with an increase in acid concentration by 10 times (0.5 – 5%), the corrosion rate increased by 175%, but with a subsequent increase in concentration by another 10 times (up to 50%), the corrosion rate increased by only 14%.

Analyzing the results obtained in the context of the corrosive activity of acidic media, we tried to compare the results obtained with data on the corrosion rate of steel St3 in other acids. Comparison of the obtained results with the literature data [10] showed that the mass index of Ct3 corrosion in 0.5% solution of MK (0.38 g/m²·h) coincides with that for 0.037% HCl (0.37 g/m²·h), and the corrosion rate in 50% solution of MK (0.77 g/m²·h) is commensurate with corrosion rates of 3.7% HCl (0.72 g/m²·h) and 0.1% H₂SO₄ (0.74 g/m²·h).

It can be reasonably assumed that MK exhibits pronounced corrosion activity and that during the operation of steel St3 in environments where the synthesis of MK (lactic acid fermentation) is possible, or its use as a working medium, corrosion protection of steel equipment is necessary.

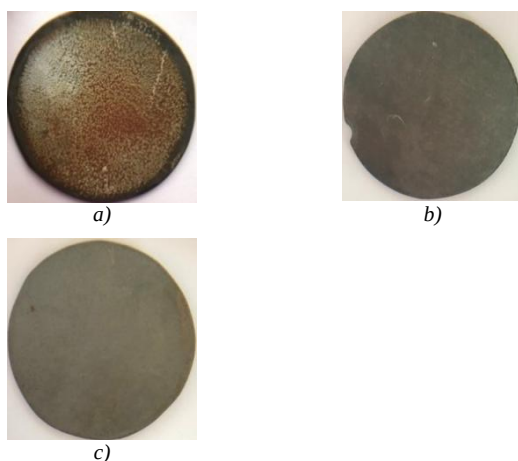
Solanine extract, the mass fraction of which in the samples was only about 0.005% (in terms of the target substance), inhibited the corrosion of the samples in all variants of the experiments. Under the influence of the indicated dose of the drug, the corrosion rate in 0.5%, 5%, 50% solutions of MK was 35%, 30%, 44% of the control, respectively (experiment 1). We obtained similar results in experiment 2, where the corrosion rate under the influence of solanine, when applied to a metal surface, was suppressed by 67%, 68% and 47% in 0.5%, 5% and 50% solutions of MK, respectively (Table 2).

Table 2: The effect of solanine extract on the volume and mass indicators of the corrosion rate of St3 in MK solutions

MK concentration	Variants of experiments	Volumetric corrosion index $K_v(H_2)$, $cm^3/m^2 \cdot h$	Mass corrosion index K_m , $g/m^2 \cdot h$
0,5%	control	153	0,38
	experience 1	53	0,13
	experience 2	50	0,13
5%	control	268	0,67
	experience 1	82	0,21
	experience 2	58	0,14
50%	control	306	0,77
	experience 1	135	0,34
	experience 2	162	0,40

It is important to note that solanine properties such as basicity and surface activity meet the requirements for modern corrosion inhibitors. The presence of an unshared electron pair on the nitrogen atom and a volumetric hydrocarbon radical in the molecule makes it possible to classify solanine as a mixed-type inhibitor [11]. The probable mechanism of corrosion inhibition revealed in our experiments may include chemisorption of solanine on the surface of steel, followed by blocking the penetration of hydroxonium ions to the metal surface.

Figure 3 shows photographs of St3 steel prototypes in MK solutions with a mass fraction of 50%. A large area of uniform corrosion of control samples under the influence of MK is visually noticeable (Figure 4a) and the absence of traces of corrosion on the test samples (Figure 4b, figure 4c).



a) control sample (50% lactic acid); b) prototype (50% lactic acid + solanine extract); c) prototype (50% lactic acid + solanine layer)

Figure 4 Control and experimental samples

The effectiveness of the anticorrosive properties of solanine was evaluated by the degree of protection (Z), as well as by the inhibitory effect (γ). Calculations of the values of Z and γ showed the greatest effectiveness of solanine in 5% MK when applied directly to the plate. The degree of protection of the St3 samples was 78%, while the corrosion rate decreased by 4.6 times. Significant, though somewhat less significant values of Z and γ are shown in the remaining variants of the experiment using solanine extract (Table 3).

Table 3: Degree of protection and corrosion inhibition coefficient St3 in MK under the influence of solanine extract

	0.5% lactic acid solution		5% lactic acid solution		50% lactic acid solution	
	Z (%)	γ	Z (%)	γ	Z (%)	γ
experience 1	65	2,9	69	3,3	56	2,3
experience 2	67	3,1	78	4,6	47	1,9

In order to confirm the data obtained indicating the effectiveness of solanine as an inhibitor of acid corrosion St3, we conducted experiments using hydrochloric acid as a corrosive medium. The experimental samples were treated with corned beef extract in the same way as in Experiment 2. The results demonstrated that the inhibitory effect of solanine is also manifested in hydrochloric acid. Exposure of samples in a solution with HCl (0.56 mol/L) for 24 hours resulted in a 2.54-fold decrease in the corrosion rate. Thus, the volumetric corrosion index in the experiment was $486.5 \text{ cm}^3/m^2 \cdot h$ versus $1238 \text{ cm}^3/m^2 \cdot h$ in the control; the mass index is $1.2 \text{ g/m}^2 \cdot h$ and $3.1 \text{ g/m}^2 \cdot h$, respectively. The degree of protection (Z) was 61%.

4. Conclusion

The results of the study allow us to speak about the pronounced corrosion activity of MK, on the one hand, and about the protective effect of solanine against acid corrosion of St3, on the other. Maintaining the focus of further research and solving specific issues, such as selecting the optimal concentrations of solanine, determining the duration of its inhibitory effect, etc., can be productive for protecting the working surfaces of machine parts from corrosion. The conducted researches can be useful for machine-building enterprises.

5. References

- Ivanov, E.S. Metal corrosion inhibitors in acidic media : handbook / E.S. Ivanov. – M.: Metallurgy, 1986. – 175 p.
- Samuylenko, A.Ya. Trends in the development of lactic acid production / A.Ya. Samuylenko, S.A. Grin [et al.] // Bulletin of Kazan Technological University. – Kazan, 2017. – Vol. 20, No. 1. – P. 162-166.
- MAS Albion [Electronic resource]. – Access mode: <https://albionchem.ru/news/14809/>. – Access date: 09.24.2022.
- Inoxpark [Electronic resource]. – Access mode: <https://www.inoxpark.ru/info/characteristics/>. – Access date: 10.09.2022.
- Metalloy [Electronic resource]. – Access mode: <https://metalloy.ru/obrabotka/chistka/metalla-kislotoy> – Access date: 03.10.2022.
- Batsko, Yu.I. The problem of corrosion of sugar factories equipment and ways to solve it / Yu.I. Batsko, R.S. Reshetova // Sugar. – M., 2022. – No. 4. – P. 16–18.
- All about corrosion [Electronic resource]. – Access mode: <https://www.okorrozii.com/korrozia-v-kislota.html>. – Access date: 27.10.2022.
- Culinary Library [Electronic resource]. – Access mode: <http://knigakulinara.ru/books/item>. – Access date: 15.10.2022.
- Orlin N.A., Razumova S.S. Isolation of saponins from the peel of green potatoes // International Journal of Applied and Fundamental Research. – 2011. – No. 6. – P. 154–154.
- Figiliantov, A.P. Corrosion protection of low-carbon steel in acidic media with inhibitors of the Sonkor A.V. series / A.P. Figiliantov, A.V. Melnikova, A.B. Shein // Izvestiya vysshikh uchebnykh zavody. Chemistry and chemical technology. – Ivanovo, 2015. – Vol. 58, No. 11. – P. 61–65.
- Kozlova, L. S. Corrosion inhibitors (review) / L. S. Kozlova, S. V. Chesnokov, A. E. Kutyrev // Aviation materials and technologies. – 2015. – No. 2. – P. 67–75.

Complex electrical impedance and dielectric spectroscopy studies of BaTiO₃-BaSnO₃ ceramics obtained via sol-gel method.

Mihaela Aleksandrova¹, Lyuben Lakov¹, Yordan Marinov², Vladimir Petkov¹, Bojidar Jivov¹, Geordi Hadjichristov²

¹Bulgarian Academy of Sciences, Institute of Metal Science, Equipment and Technologies with Hydro- and Aerodynamics Centre "Acad. A. Balevski", Shipchenski Prohod Blvd. 67, 1574 Sofia, Bulgaria, e-mail: mihaela.krasimirova@mail.bg

²Bulgarian Academy of Sciences, Institute of Solid State Physics "G. Nadjakov", 72 Tzarigradsko Chaussee, Blvd., 1784 Sofia, BULGARIA

Abstract: In view of the practical applications of the piezoelectric ceramics produced from barium titanate (BaTiO₃) and barium stannate (BaSnO₃), (the BT-BS system), the dielectric behavior of such materials was studied. The starting components (powder of both BaTiO₃ and BaSnO₃) were synthesized and structurally characterized in advance. Bulk samples of BT-BS (formed as tablets with addition of PVA plasticizer) were prepared using the sol-gel method by varying the BT-BS composition percentage. The samples were characterized by complex electrical impedance spectroscopy and dielectric spectroscopy in the frequency range from 0.1 Hz to 1 MHz. As compared to BaTiO₃, an increase with at least 50 % was measured for the value of the room-temperature dielectric constant (ϵ' – the real part of the dielectric permittivity) of the BT-BS samples containing 15 wt% BaSnO₃. In contrast, the 50 wt% content of BaSnO₃ led to a decrease of ϵ' value of BT-BS by a factor of 3.5, due to relatively low ϵ' value of BaSnO₃. Analyses of the frequency spectra of complex electrical impedance and complex dielectric permittivity revealed the dielectric relaxational behavior of the BaTiO₃+BaSnO₃ system. The results obtained for ϵ' of BT-BS dielectrics as a function of the temperature were correlated with the data from structural studies. In particular, a specific enhancement of ϵ' was observed in temperature range around 120 °C for the BT-BS samples containing 15 wt% BaSnO₃. Corresponding conclusions were done. The effects observed show that the synthesized BaTiO₃-BaSnO₃ ceramics are promising materials for piezoelectric and dielectric applications, e.g., in energy storage devices.

Keywords: SOL-GEL, BATIO₃, BASNO₃, IMPEDANCE SPECTROSCOPY

I. Introduction

Alkaline earth mites are interesting compounds in terms of their dielectric properties. Solid solutions in the BaTiO₃-BaSnO₃ (BTBS) system have attracted attention in recent years in the field of nanocapacitors. Synthetic BaTiO₃, prepared by conventional solid phase method shows great performance with high ϵ_r value of ~ 1900 at room temperature (30 °C), low dielectric loss $\delta \sim 0,01$ and piezoelectric constant $d_{33} \sim 191$ pC/N [1]. BaTiO₃ has five polymorphic structures showing different phases that vary with temperature [2]. The phase transition of BaTiO₃ at the Curie temperature (T_c) significantly changes its properties, which are ferroelectric and non-ferroelectric.

The BaTiO₃ nephroelectric shows a hexagonal structure at 1460 °C and a cubic structure at over 120 °C [3]. On the other hand, the ferroelectric properties of BaTiO₃ exist in three different polymorphic crystal structures, which are tetragonal, orthorhombic and rhombohedral. Zheng et al. [4] studied the effect of grain size on the dielectric constant and piezoelectric properties of BaTiO₃. They report that the dielectric constant and piezoelectric properties increase significantly by reducing the grain size. The maximum grain size was reached around 0.94 μm due to the density of the domain structure and the area decreased with decreasing grain size. BaSnO₃ has a cubic perovskite structure that exhibits n-type semiconductor behavior at room temperature [5, 6]. BaSnO₃ is thermally stable up to 2000 °C, but has a high absorption of moisture compared to other species [6]. Thus, it is currently used for thermally stable capacitors and humidity sensors [7, 8]. Meanwhile, completely dense BaSnO₃ ceramics can be achieved by synthesizing them at temperatures above 1594 °C [6]. Huang reported that in order to obtain single-phase BaSnO₃, it is necessary to heat it to 1200 °C and achieve a significant amount of grain porosity [9, 10].

In addition, Azad confirmed that grain porosity can be reduced by milling BaSnO₃ at 1600 °C [11]. The initial report on materials based on the findings found that BaSnO₃, synthesized at 1200 °C, has a dielectric constant $\epsilon_r \sim 14$ at 25 °C [6]. Kumar reported that BaSnO₃ was sintered at 1200 °C for 12 hours using the solid state method. A huge dielectric behavior of BaSnO₃ has recently emerged, where the dielectric constant ϵ_r value reaches ~ 6000

when measured at 220 °C and at a frequency of 1 kHz. The ϵ_r value of BaSnO₃ is two orders of magnitude higher than previously reported studies [12, 13]. However, the dielectric constant decreases with decreasing temperature. Therefore, it is assumed that the lack of oxygen leads to a reduction of Sn⁴⁺ to Sn²⁺ in BaSnO₃ samples, which contributes to an anomaly in the value of the giant dielectric constant ϵ_r when the samples were sintered at very high temperatures of $T^\circ\text{C} \geq 1450^\circ\text{C}$ [13-16].

II. Experimental part

Organic precursors such as barium acetate, titanium butoxide and stannous acetate were used to synthesize the ceramic samples. The process is carried out according to the sol-gel method, with the ratio of the starting components being 1:1:1.6. The solutions were prepared in the presence of acetic acid, distilled water and acetylacetone. Each of the indicated solutions was homogenized independently using a magnetic stirrer for 30 minutes. After mixing the components, the total solution was homogenized for 5 hours. The synthesis and stabilization of the sol thus carried out allows the deposition of thin layers on various monolithic substrates. One part is allowed to gel. The gel was dried in an oven at 120 °C for 24 hours. Next is annealing at 800 °C and holding for 8 hours. After obtaining the desired BaTiO₃ and BaSnO₃ phases, tablets are formed and pressed in the presence of polyvinyl alcohol. The finished samples are calcined in a furnace at a temperature of 1100 °C until the plasticizer burns out. The deposition of layers by the immersion method is carried out by means of a dip-coater

III. Results and discussion

Characterization of the resulting phases was performed by X-ray analysis using a Bruker D8 Advance automatic powder X-ray diffractometer with CuK α radiation (Ni filter) and registration by a LynxEye solid-state detector. The X-ray spectrum was recorded in the angular range from 10 to 80° 2 θ with a step of 0.02° 2 θ and a counting time of 17.5 s/step. Qualitative phase analysis was performed using the International Center for Diffraction Data (ICDD) PDF-2(2022) database. In fig. 1 and 2 are presented X-ray photographs of the prepared samples of BaTiO₃-BaSnO₃ in the ratio (85%:15%) and BaTiO₃-BaSnO₃ in the ratio (50%:50%). Figure 2 shows the distinct peaks of the BaTiO₃ and BaSnO₃ phases. We

have the presence of TiO_2 in two nonstoichiometric compositions between 24° and 25° and nonstoichiometric SnO_2 at 27° . The result may be due to the not good homogeneity during the preparation of the tabled samples or incorrectly conducted temperature mode of baking. When adjusting the percentage ratio of the BaTiO_3 - BaSnO_3 system (85%:15%), we have a monophasic characteristic of the BaTiO_3 - BaSnO_3 structure.

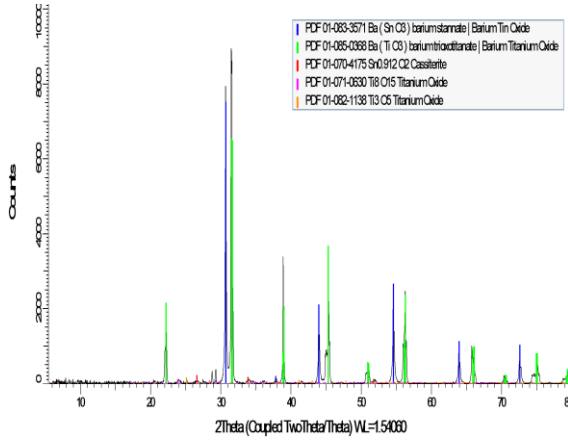


Fig. 1. System $\text{BaTiO}_3 + \text{BaSnO}_3$ in ratio (50% : 50%) ceramic

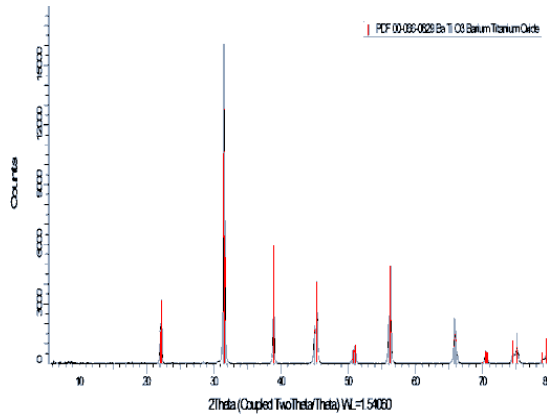


Fig. 2. System $\text{BaTiO}_3 + \text{BaSnO}_3$ in ratio (85% : 15%) ceramic

Description of impedance spectra

Experimental data were obtained by EIS. By this technique, both real ($\text{Re}Z$) and imaginary ($\text{Im}Z$) parts of the complex electrical impedance $Z^* = \text{Re}Z + i \text{Im}Z$ are simultaneously measured as a function of the frequency f of the alternating-current (AC) electric field applied. The frequency spectra of Z^* of the produced sample were recorded by electrical impedance-meter Bio-Logic SP-200, in the range 0.1 Hz – 1 MHz, at various temperatures (Fig.4). By the measurements, for all the samples were kept identical experimental conditions. Silver paste was applied on both sample surfaces, serving as electrodes. The amplitude of the AC voltage applied between the electrodes of ceramic cylinders was 2 V_{RMS} (sine function). The dimensions of the two round electrodes were 2.0 cm in diameter, the distance between them varied 1-4 mm.

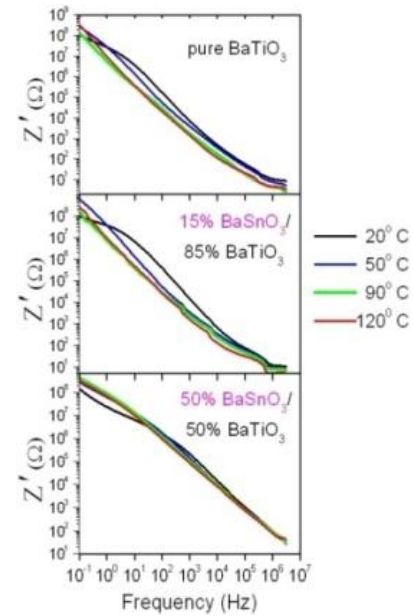
Dielectric Spectroscopic Analysis

Dielectric Permittivity

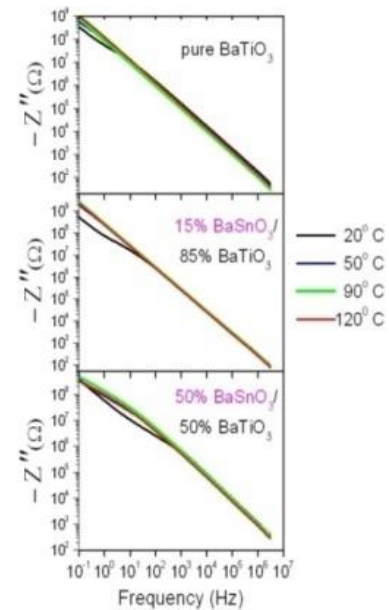
By means of the expressions

$$\epsilon'(f) = \frac{-Z''(f)d}{2\pi f \epsilon_0 A |Z(f)|^2} \text{ and } \epsilon''(f) = \frac{Z'(f)d}{2\pi f \epsilon_0 A |Z(f)|^2}$$

from the measured $Z'(f)$ and $Z''(f)$ spectra, we calculated the real (ϵ') and imaginary (ϵ'') parts of the complex dielectric function of the composites under study. The geometrical parameters were $A = XX \text{ cm}^2$ and $d = XX \text{ mm}$, and $\epsilon_0 = 8.85 \times 10^{-12} \text{ F.m}^{-1}$ was the value of the permittivity of free space. The dispersion curves for both ϵ' and ϵ'' had relaxational characteristics.



a)



b)

Fig. 4 Frequency spectra of real (Z') and imaginary (Z'') parts of complex electrical impedance measured for the samples at different temperatures

Conclusion:

BaTiO₃-BaSnO₃ ceramic phases were synthesized. XRD analysis showed a good phase structure in the ratio of 85%/ 15%. The studied physical and mathematical indicators showed good piezoelectric effects. With a view to future applications in electronics, the material will be further investigated both as dip-coating deposited thin layers and presented in subsequent developments by the team.

Acknowledgements

The authors are grateful to the financial support of the Bulgarian National Science Fund at the Ministry of Education and Science, Contract No KP-06-Russian/18 or 15.12.2020 for the opportunity to carry out the necessary research.

Part of the team are grateful to the financial support of Bulgarian National Science Fund at the Ministry of Education and Science, Contract No KII-06-H 37/26 18.12.2019 for the opportunity to present the results at an international conference.

References:

1. Eric A. Gabilondo, Shaun O'Donnell, Rachel Broughton, Jacob L. Jones, Paul A. Maggard, "Synthesis and stability of Sn (II)-containing perovskites: (Ba,SnII)HfIVO₃ versus (Ba,SnII)SnIVO₃", *Journal of Solid State Chemistry*, (2021), 302.
2. Amine Bendahhou, Pascal Marchet, Soufian El Barkany, Mohamed Abou-Salama, "Structural and impedance spectroscopic study of Zn-substituted Ba₅CaTi₂Nb₈O₃₀ tetragonal tungsten bronze ceramics", *Journal of Alloys and Compounds*, Elsevier, 2021, 882, pp.160-176.
3. Jinyu Lu, Gang He 1, Jin Yan, Zhenxiang Dai , Ganhong Zheng 1, Shanshan Jiang, Lesheng Qiao, Qian Gao, Zebo Fang, "Interface Optimization and Transport Modulation of Sm₂O₃/InP Metal Oxide Semiconductor Capacitors with Atomic Layer Deposition-Derived Laminated Interlayer", *Journal Nanomaterials*, 2021, 11, 3443.
4. Fayaz Hussain, Amir Khesro, Raz Muhammad, Dawei Wang, "Effect of Ta-doping on functional properties of K_{0.51}Na_{0.49}NbO₃", 2019, *Materials Research Express* 6, 106309.
5. Kezhen Yin, Jingwei Zhang, Zhenpeng Li, Jingxing Feng, Ci Zhang, Xinyue Chen, Andrew Olah, Donald E. Schuele, Lei Zhu , Eric Baer, "Polymer multilayer films for high temperature capacitor application", *Journal of applied polymer science*, 2018, DOI: 10.1002/app.47535.
6. Dong, N., Gao, X., Xia, F., Liu, H., Hao, H. & Zhang, S. (2019). Dielectric and Piezoelectric Properties of Textured Lead-Free Na_{0.5}Bi_{0.5}TiO₃-Based Ceramics. *Crystals*, 9 (4), 9040206-1-9040206-11.
7. L. Zhang, Y. Pu, M. Chen, Ultra-high energy storage performance under low electric fields in Na_{0.5}Bi_{0.5}TiO₃-based relaxor ferroelectrics for pulse capacitor applications, *Ceram. Int.* 46 (2020) 98–105. <https://doi.org/10.1016/j.ceramint.2019.08.238>.
8. Hend Kacem, Ah. Dhahri, Mohamed Amara Gdaiem, Z. Sassi, L. Seveyrat, L. Lebrun, V. Perrin, J. Dhahri, "Electrocaloric properties of lead-free ferroelectric ceramic near room temperature", *Applied Physics A* (2021) pp127:483.
9. Dash Smaranika, Pradhan Dhiren K., Kumari Shalini, Ravikant None, Rahaman Md. Mijanur, Cazorla C., Brajesh Kumar, Kumar Ashok, Thomas Reji, Rack Philip D., Pradhan Dillip K., "Enhanced ferroelectric and piezoelectric properties of BCT-BZT at the morphotropic phase boundary driven by the coexistence of phases with different symmetries", (2021) *Physical Review B*, Volume: 104; Journal Issue: 22.
10. Luo Huajie, Qi He, Sun Shengdong, Wang Lu, Ren Yang, Liu Hui, Deng Shiqing Chen Jun, Structural origin for the high piezoelectric performance of (Na_{0.5}Bi_{0.5})TiO₃-BaTiO₃-BiAlO₃ lead-free ceramics, *Journal Acta Materialia* Volume: 218, (2021) doi.org/10.1016/j.actamat.2021.117202.
11. F Medjaldi, A Bouabellou, Y Bouachiba, A Taabouche, K Bouatia and H Serrar, "Study of TiO₂, SnO₂ and nanocomposites TiO₂:SnO₂ thin films prepared by sol-gel method: Successful elaboration of variable- refractive index system", *Mater. Res. Express* 7 (2020) 016439.
12. B. Wodecka-Du's, M. Adamczyk-Habajska, T. Goryczka, D. Bochenek, "Chemical and Physical Properties of the BLT4 Ultra Capacitor—A Suitable Material for Ultracapacitors", *Materials* 2020, 13, 659; doi: 10.3390/ma13030659.
13. Tae Yeon Kim, Je Oh Choi, Gopinathan Anoop, Jaegyu Kim, Seong Min Park, Shibnath Samanta, Woosoon Choi, Young-Min Kim, Seungbum Hong , Ji Young Jo, "(111)-oriented Sn-doped BaTiO₃ epitaxial thin films for ultrahigh energy density capacitors", *Ceramics International*, Available online 15 June 2021, 0272-8842.
14. Lyuben Lakov, Mihaela Aleksandrova, Vladimir Blaskov, Yordan Marinov, Veselin Petkov, „Technological regulation for creating a ceramic target from BaTiO₃ gel powders doped with Sn. Temperature dependence of the dielectric permittivity", *Machines. Technologies. Materials*. Vol. 15 (2021), Issue 4, pg(s) 155-157.
15. Mihaela Aleksandrova, Bojidar Jivov, Lyuben Lakov, „Summary of sol-gel synthesis of materials with electronic applications", *International Scientific Journal Materials Science. Non-Equilibrium Phase Transformations*, Year VI, Issue 3 / 2020, Scientific Technical Union of Mechanical Engineering INDUSTRY 4.0, 2020, ISSN:ISSN PRINT 2367-749X, ISSN WEB 2534-8477, 83-85.
16. Ku Noor Dhaniah Ku Muhsen, Rozana Aina Maulat Osman, Mohd Sobri Idris, "The effects of Ca, Zr and Sn substitutions into a ternary system of BaTiO₃-BaSnO₃-BaZrO₃ towards its dielectric and piezoelectric properties": a review, *Journal of Materials Science: Materials in Electronics*, Published online, june 2020.

Study of aluminum content on the structure and phase composition of synthesized aluminum-matrix composites

Yevheniia Kyryliuk, Genadii Bagliuk, Stepan Kyryliuk, Bykov Oleksandr, Yulia Shishkina
Frantsevich Institute for Problems in Materials Science, NASU, Kyiv, Ukraine, 03142, Krzhizhanovsky str., 3

Abstract: The work shows that there is no significant change in the phase composition of composites with a change in the synthesis temperature, so we can use pre-synthesized heats at a temperature of 950 °C to obtain hot-stamped aluminum-based composites. The best characteristics of the synthesized titanium carbide were obtained for the composition 45Al-11C-44Ti (% wt.). The lattice period of titanium carbide for this sample is 0.4324, and the particle size of titanium carbide formed after sintering is 0.8-1.5 μm. The influence of the component composition of the initial charge on the features of the structure and the phase composition of the thermally synthesized heat of the Al-C-Ti system was established.

KEYWORDS: THERMAL SYNTHESIS, MASTER ALLOY, METAL MATRIX COMPOSITE, ALUMINUM, STRUCTURE, PHASE COMPOSITION, TITANIUM CARBIDE, LATTICE SPACING.

Today, aluminum matrix composites (AMC) have found the most effective application in automotive, aviation and rocket engineering [1, 2]. This is explained by their low weight, high mechanical, tribotechnical and corrosion properties. The most widely used AMCs are reinforced with ceramic particles, since they have isotropic properties and are made according to a simpler and cheaper technology compared to fibrous and layered aluminum composites. Ceramic powders of aluminum oxide (Al₂O₃) and silicon carbide (SiC) with a size of 10-20 μm with a volume fraction of up to 25% are used as a reinforced phase in most of the manufactured AMCs. However, in recent years, attention has been paid to the use of titanium carbide (TiC) as a dispersion-strengthened phase, since TiC particles can provide AMC with a complex of properties, surpassing all other discretely strengthened AMC [3]. This is due to the fact that TiC has an fcc crystal lattice that coincides with the α-Al crystal lattice, as well as high strength, hardness, and thermodynamic stability. Both powder metallurgy and casting methods are applicable for the production of Al/TiC composites [4]. All these methods can be divided into ex-situ methods, when the reinforced particles are produced in advance, separately, outside the matrix, and then introduced into the matrix during the manufacturing process of the composite, and in-situ methods, when the reinforcing particles are synthesized by chemical reactions directly in the matrix during preparation of the composite. In the case of ex-situ methods, the surface of the powders is usually contaminated with oxides, moisture, adsorbed gases, which impair the wettability of the powders by the matrix and the adhesion between the particles and the matrix. In the case of in-situ methods, the reinforcing particles synthesized in the matrix have a clean, uncontaminated surface, which is important for ensuring strong adhesion to the matrix, they are thermodynamically stable and do not replay with the matrix, they can have a smaller size and a more uniform distribution in the matrix [5, 6], thanks to these advantages, in-situ methods are currently being intensively developed.

Therefore, promising for Al-Ti-C aluminum composites is the direction associated with the preliminary synthesis of titanium carbide in a powder mixture. Depending on the ratio of the content of titanium and carbon in the mixture, when it is heated, in-situ formation of dispersed particles of titanium carbide and ternary titanium carbide occurs, which allows you to control their dispersion and shape. Titanium carbide does not interact with the aluminum matrix and does not form undesirable compounds.

As a result of previous studies [7-10], the authors have accumulated and systematized a certain amount of information on obtaining new composite materials, technologies for preparing powder mixtures (mechanical methods: grinding, chemo-thermal methods: processing in argon and vacuum), consolidation conditions (sintering in controlled gas environments, hot pressing and stamping), which will create new powder composite materials.

The purpose of the work is to study the phase and structure formation of aluminomatrix composite materials strengthened by titanium carbide during their thermal synthesis, as well as to study

the influence of the phase composition of composites on the synthesis temperature.

The achievement of the set goal will occur as a result of using the effects of obtaining the required dispersed phases during thermal synthesis, which will allow to purposefully influence the growth rate of grains and artificially create heterogeneity of the composite and thereby form a fine-grained microheterogeneous structure with high physical, mechanical and tribotechnical properties. A new approach in the creation of such powder materials is that refractory reinforcing additives can be formed by recrystallization in thermal synthesis from elementary powders.

Objects and research methods

Aluminum, titanium and graphite powders were used as raw materials for preparing the charge mixture which was subsequently thermally synthesized. To evaluate the effect of blending ratio on the structure and properties of the samples after sintering four compounds of row charge mixtures were chosen. The materials used in this study are summarized in Table 1.

Table 1 - Chemical composition of charge mixtures for the synthesis of composites

Number	Composition, % (mass.)		
	Al	C	Ti
1	45	11	44
2	50	10	40
3	55	9	36
4	60	8	32

The initial mixtures were pressed under a pressure of 500 MPa, thermal synthesis was carried out in a vacuum furnace of induction heating at a temperature of 950 °C and held for 1 hour with a sintering rate of 5-10 degrees./min. Composites was studied using a scanning electron microscope with an energy-dispersive microanalyzer REM 106i, which allows obtaining images of the structure with high spatial resolution and depth of field in reflected (BSE) and secondary (SE) electrons, as well as provides information about the chemical composition and structure. Etching of the samples was performed in a 40% NaOH solution. Microspectral analysis, X-ray phase analysis and differential thermal analysis (DTA) was also performed.

Results and discussion

The composition of powder mixtures used for the synthesis of Al-Ti-C composites is shown in Table. 1. as a result of synthesis, the initial samples (fig. 1. b, c) turned into fairly strong and relatively dense compacts. After sintering, there was no significant increase in volume and no change in the shape of the compacts due to thermal synthesis at a low heating rate of 5-10 degrees/min. The

advantage of this method is the production of dispersed particles of titanium carbide in the aluminum matrix as a result of the in-situ reaction between the original elementary powders of Al, Ti and C. It is assumed that as a result of the in-situ reaction during the synthesis of the material, the intergrain boundaries between the particles of the strengthening phase and aluminum will be free from oxides, which significantly increases the interfacial strength, and the titanium carbide particles themselves will have a submicron size and a fairly homogeneous volume distribution, which leads to an increase in the mechanical properties of the composite [11, 12].

By adjusting the heating rate, the final porosity of the synthesized compacts can be controlled. The porosity of the synthesized composites varies from 8 to 25%, depending on the aluminum content (45-60% by mass) and the sintering rate from 5 to 10 degrees/min.

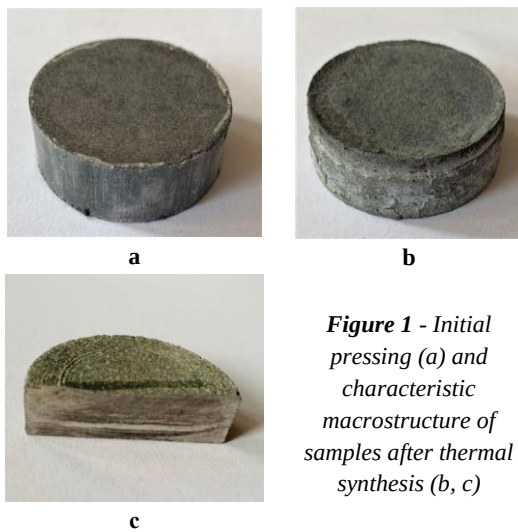
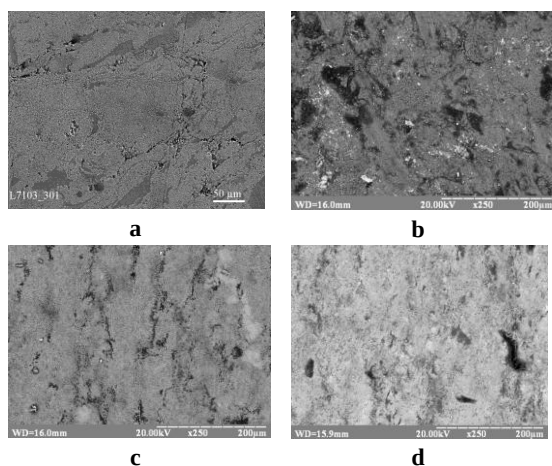


Figure 1 - Initial pressing (a) and characteristic macrostructure of samples after thermal synthesis (b, c)

The results of scanning electron microscopy (SEM) of the samples after thermal synthesis presented in Figure 2 and show that the studied samples have mainly a two-phase structure - a gray field, on which light small particles are evenly distributed. It should be noted that the number of light particles significantly decreases with the increase in the amount of aluminum in the samples.

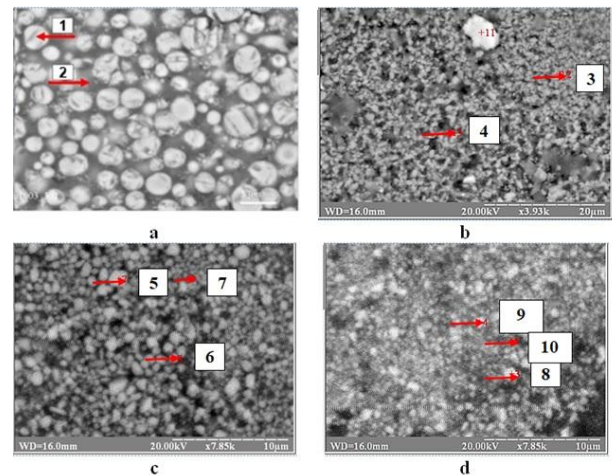


a – 45Al-11C-44Ti (% , mac.); b – 50Al-10C-40Ti (% , mac.);
c – 55Al-9C-36Ti (% , mac.); d – 60Al-8C-32Ti (% , mac.)

Fig. 2 - SEM microstructure of Al-Ti-C composites after thermal synthesis

Quantitative analysis showed that the gray field in the photographs of microstructures (Fig. 3) consists mainly of aluminum (Table 2, spectra 2), or a mixture of aluminum and

titanium carbide particles (spectra 4, 7-10), light rounded particles (spectra 3, 5 and 6) correspond to the close to stoichiometric composition of titanium carbide. In addition, an increase in the amount of aluminum from 45 to 60% leads to an increase of oxygen in the samples, the percentage of which gradually increases in the samples 55Al-9C-36Ti (% , wt.) and 60Al-8C-32Ti (% , wt.).



a – 45Al-11C-44Ti (% , mac.); b – 50Al-10C-40Ti (% , mac.);
c – 55Al-9C-36Ti (% , mac.); d – 60Al-8C-32Ti (% , mac.)

Fig. 3 -.SEM microstructure of Al-Ti-C composites after thermal synthesis

Table 2 - Content (wt.) of elements at different points synthesized ligatures of the Al-Ti-C system (see Fig. 2)

№ spectrum	Al, %	Ti, %	C, %	O, %
1	30,33	60,36	9,3	-
2	55,1	44,1	3,86	-
3	15,48	47,01	24,26	13,25
4	30,91	26,18	31,36	11,55
5	8,94	55,40	22,70	12,97
6	20,56	45,38	16,33	17,73
7	21,5	41,60	23,66	13,24
8	35,75	25,06	20,57	19,62
9	35,91	30,13	17,52	16,44
10	45,19	23,52	18,07	13,20

The dispersion of titanium carbide particles in the sample with the composition 45Al-11C-44Ti (% , wt.) lies in the range from 0.8 to 1.5 μm (Fig. 3, a), which is less than in other samples in which the grain size 2-4 μm, respectively (Fig. 3, b - d).

This is explained by the different content of aluminum: the greater its amount surrounds the titanium carbide particles formed in the synthesis process, the larger the diffusion path becomes and the smaller the driving force that promotes the growth of the particles.

Fig. 4 presents the XRD pattern of initial mixture and composites. It can be seen that the initial mixture contains Al, Ti and C as shown in Fig 4a. The XRD results revealed the presents of TiC and Al in all specimens Fig 4 (b, c, d, e)

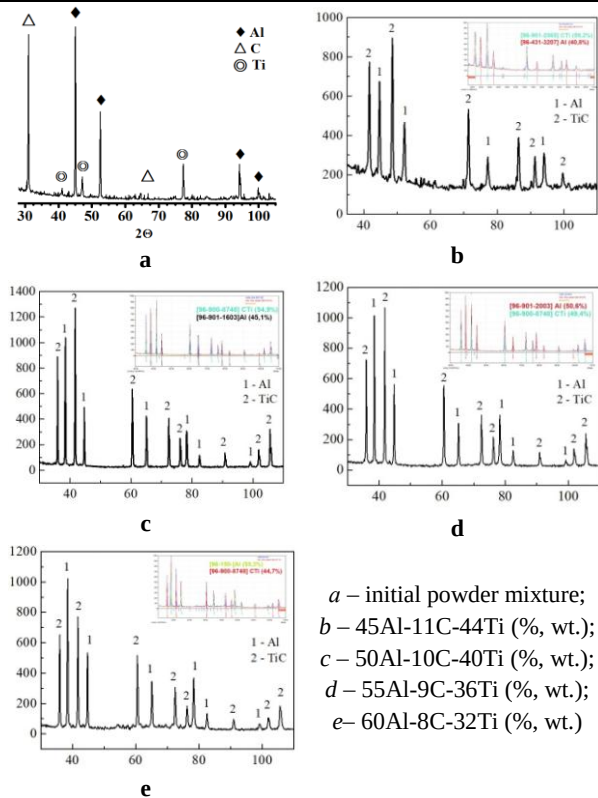


Fig. 4 - Diffraction patterns of the initial powder mixture (a) and synthesized Al-Ti-C master alloys (b, c, d, e)

The influence of the aluminum content on the parameters of the titanium carbide lattice was investigated (Fig. 5). In all samples, the diffraction lines of titanium carbide are at approximately the same angle, which explains the close values of the period of the TiC lattice (Fig. 5).

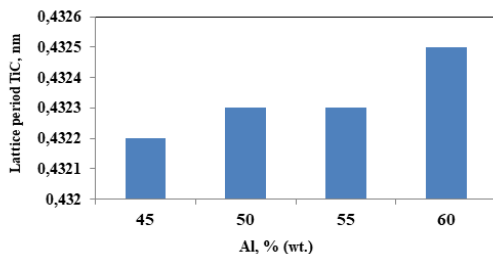


Fig. 5 - The value of the period of the TiC lattice on the content of aluminum in composites

However, it should be noted that with an increase in the amount of aluminum in the samples, it can be seen that the value of the lattice period increases. The low value of the period of the TiC lattice may be related to too little amount of aluminum, which in this system at the synthesis temperature of 950 °C is an environment that facilitates the interaction between titanium and carbon, and its deficiency affects the completeness of the carbide formation reaction.

The differential thermal analysis of the studied systems showed that for all compositions of the initial mixtures, the DTA curves have pronounced endothermic and exothermic peaks (Fig. 6). For samples with a content of 50 and 60 wt. % aluminum, the minima of the endothermic and the maxima of the exothermic peaks practically coincide (at temperatures of about 640 °C and 800 °C, respectively). In a sample with a content of 45 wt. % of aluminum,

endothermic peaks with minima at 635 °C are observed, and exothermic peak maxima correspond to temperatures of 812 °C and 800 °C. The endothermic effect at temperatures of 635 - 675 °C is explained by the appearance of a liquid phase. The exothermic peaks on the DTA curves at 800 °C and 812 °C correspond to the in-situ formation of titanium carbide as a result of the solid-phase interaction of titanium with carbon, where the aluminum melt acts as a medium that intensifies the formation of titanium carbide. Based on the fact that this reaction is one of the most thermodynamically advantageous, it can be assumed that the formation of titanium carbide proceeds in this way. The temperature of formation of TiC on DTA may be underestimated, because measurements of a small mass were used for the research. During the synthesis of ligatures, heating of the presses to an average of 1100 °C was recorded.

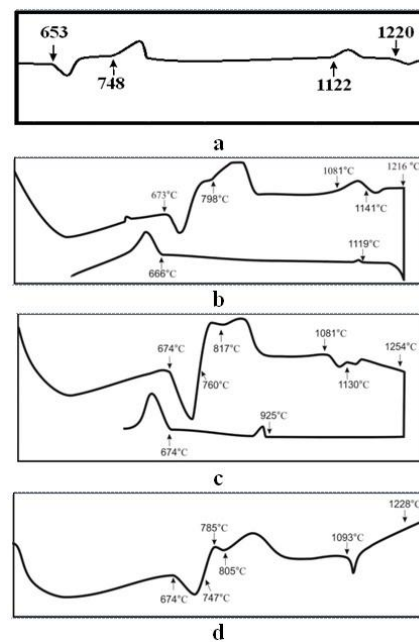


Fig. 6 -.Differential thermal analysis of Al-Ti-C powder mixture

Thus, the results of microspectral analysis, X-ray phase analysis, and differential thermal analysis of samples obtained by thermal synthesis from powder mixtures of different compositions made it possible to establish that for all investigated compositions of the starting mixtures, when they are heated, in-situ separation of TiC titanium carbide particles occurs. The alloys synthesized from a mixture of the compositions 45Al-11C-44Ti (% wt.) and 50Al-10C-40Ti (% wt.) are characterized by the greatest dispersion of the particles of the strengthening phase, which were chosen for obtaining aluminum composites by the method of hot stamping, together with the sample composition 60Al-8C-32Ti (% wt.), in which complex titanium carbide appears.

Conclusions

1 The results of microspectral analysis, X-ray phase analysis, and differential thermal analysis of samples synthesized from powder mixtures of different compositions made it possible to establish that for all the compositions of the initial mixtures, upon

heating, in-situ formation of TiC titanium carbide particles and a small amount of titanium aluminides occurs.

2. It is shown that there is no significant change in the phase composition of the composites with a change in the synthesis temperature, therefore, in the future, we can use pre-synthesized heats at a temperature of 950 °C to obtain hot-forged aluminum-based composites. The best characteristics of the synthesized titanium carbide were obtained for the composition 45Al-11C-44Ti (% wt.). The lattice period of titanium carbide for this sample is 0.4324, and the particle size of titanium carbide formed after sintering is 0.8-1.5 µm.

3. The influence of the component composition of the initial charge on the structural features and phase composition of the thermally synthesized heat of the Al-C-Ti system was determined. It is shown that in the case of using a charge with a stoichiometric carbon content in relation to titanium, the predominant strengthening phase of the alloy is titanium carbide.

References

1. Kainer K.U. Metal Matrix Composites // Weinheim, Germany: Verlag GmbH & Co. KGaA, 2006.
2. Adebisi A.A., Maleque M.A., Rahman Md.M. Metal matrix composite brake rotor: historical development and product life cycle analysis. International Journal of Automotive and Mechanical Engineering. – 2011. – Vol. 4. – p. 471 – 480.
3. Амосов, А.П., Луц А.Р., Латухин Е.И., Ермошкин А.А. Применение процессов СВС для получения in-situ алюмоматричных композиционных материалов, дискретно армированных наноразмерными керамическими частицами: обзор // Изв. Вузов. Цветная металлургия. – 2016. – №1. – С. 39-49
4. Rana R.S, Purohit R., Das S. Review of Recent Studies in Al Matrix Composites // International Journal of Scientific Engineering and Research. – 2012. – Vol. 3. – P. 1-16
5. Kennedy A.R and Wyatt S.M. Characterising particle–matrix interfacial bonding in particulate Al–TiC MMCs produced by different methods // Composites Part A: Applied Science and Manufacturing. – 2001. – Vol. 32. – Issues 3-4. – P. 555 – 559.
6. Das B., Roy S., Rai R.N., Saha S.C. Development of an in-situ synthesized multi-component reinforced Al – 4.5%Cu-TiC metal matrix composite by FAS technique – Optimization of process parameters // Eng. Sci. & Technology, an International Journal.– 2016. – Vol. 19 (1). –P. 279 – 291.
7. Баглюк, Г.А., Шишкина Ю.А. Новые композиционные дисперсно-упрочненные материалы на основе алюминия // Технологические системы. – 2011. – № 4 (57). – С. 36-43.
8. Shishkina Y., Baglyuk G., Mamonova A., Tikhonova I. Specific features of structure formation in Al-Ti-C powder master alloys after thermal synthesis // International Scientific Journal «Machines. Technolo Materials». – 2012. – Vol. 12. – P. 45-49.
9. Shishkina, Y.A. Baglyuk G.A., Mamonova A.A., Tikhonova I. B. Effect of carbon and aluminum contents on the structurization of Al–Ti–C powder master alloy during reaction synthesis // International Scientific Journal «Machines. Technologies. Materials». – 2013. – Vol 52. – No 3-4. – P. 154–160.
10. Богачева А.Г. Баглюк Г.А., Шишкина Ю.А. Получение и свойства дисперсно-упрочненных легких сплавов / А.Г. Богачева, // Технологические системы. – 2013. – № 6 (64). – С. 23-38.
11. Луц, А. Р. Самораспространяющийся высокотемпературный синтез модифицирующих лигатур и композиционных сплавов в расплаве алюминия с применением флюсов: автореф. дис. канд. техн. наук: 01.04.17 / А. Р. Луц. – Самара, 2006. – 25 с.

12. Савицкий А. П. Современные представления о спекании в жидкой фазе // А. П. Савицкий / Порошковая металлургия. – 1987. – №8. – с. 35-41.