Applied Engineering Letters Vol. 2, No 2, 69-75 (2017) e-ISSN: 2466-4847

OPTIMIZATION OF EFFICIENCY OF WORM GEAR REDUCER BY USING TAGUCHI-GREY METHOD

Slavica Miladinović[1], Saša Radosavljević[1], Sandra Veličković[1], Raed Atyat[1], Aleksandar Skulić[1], Veljko Šljivić[2]

[1] University of Kragujevac, Faculty of Engineering, Sestre Janjić 6, 34000 Kragujevac, Serbia
[2] University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, 11120 Belgrade, Serbia

Abstract:
In this paper the efficiency and output power are considered, as the most important characteristics of the worm gear reducer, and their optimization was performed. As the influencing factors, the viscosity of the lubricant, the input number of revolutions and the current intensity on the control unit, were taken into account. Experimental tests were performed on the basis of the L27 Taguchi orthogonal matrix. Due to multiple output issues, the Grey method was applied. Based on the Grey relational grade using the ANOVA analysis, the optimal combination of factors is A3B2C3 ie. Grey relational grade is the highest for the number of revolutions 2000 min-1, the viscosity of the lubricant 460 mm^2/s and current intensity of 0.2 A. Also, Grey relational grade was most influenced by the current intensity on the control unit with 72.1%.

ARTICLE HISTORY
Received 15.05.2017.
Accepted 17.06.2017.
Available 30.06.2017.

KEYWORDS
efficiency, worm gear, Taguchi-Grey analysis, optimization.

1. INTRODUCTION

The worm gear pair or the worm gear is a type of gear whose axes pass by each other, mostly at the angle of 90°. The worm gear consists of a worm wheel (1) and worm (2) shown in Figure 1. The angle at which the axis pass by each other can be greater and less than 90 °. If the driving part of the gear is a worm then the reduction of the number of revolutions is done, and if the worm wheel is a drive part then the multiplication of the number of revolutions is done [1]. The ratio of invested and useful power represents efficiency. In comparison to other type of gears, the worm gear has a lower value of the efficiency. The reason for the difference between the invested and the useful power is the power losses occurring in the gear reducer. The magnitude of the power losses of worm gears and their causes were examined by A. Skulić et al. Power losses occur during the meshing between worm wheel and worm, power losses in the bearings, seals and power losses of oil during the transmission. When the contact of the meshing between worm wheel and worm is realized along the line and when there is considerable sliding, the biggest losses occur in the meshing between worm wheel and worm. The magnitude of the losses is primarily influenced by the type of used materials and the geometry of the worm gear, the angular velocity, the type and viscosity of the lubricating oil, the load, the shape of worm, the temperature and other [2].

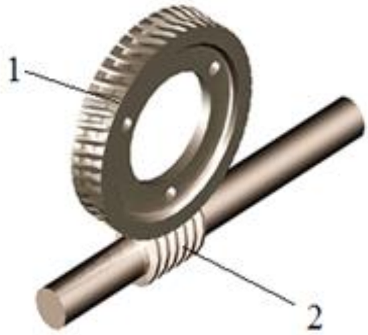


Fig.1. Worm gear

The efficiency is influenced by many factors, among which the mostly influence has type of lubricant, i.e., the viscosity of the lubricant, other influencing factors are, also, the number of velocity

CONTACT: Sandra Veličković, sandrav@kg.ac.rs

of the drive shaft, the material, the gear ratio, the axial distance, and the other. M. Turks et al. [3] carried out the determination of the efficiency of the worm reducer with a 50 mm axial distance, a gear ratio of 49, and for different types of lubricants they obtained the values of the efficiency. B. Magyar and B. Sauer [4] carried out the determination of efficiency at a lubricant temperature of 60° C and an output torque of 430 Nm for different values of the input number of revolutions. H. Siebert [5] made the determination of the influence of different types of lubricants on the efficiency of the worm reducer, with a gear ratio of 39, an input number of revolution of 350 min^{-1} and an output torque of 200 Nm.

Finding optimal combinations of influencing factors on the efficiency of the worm reducer can be done using various optimization methods. In recent years, Grey analysis has often been used in combination with the Taguchi method and is known as Taguchi-Grey analysis. This analysis is used when there are multiple test outputs. J. Sudeepan et al. examined the tribological characteristics of the composite ABS (acrylonitrile-butadiene-styrene) polymer with micro particles of calcium carbonate. As influential factors, the content of the filler, the normal load and the sliding speed were observed, while the coefficient of friction and the specific wear rate were observed as the output value. By applying Grey and ANOVA analysis, Grey relational grade was obtained for the quality characteristic lower-the-better. Optimal combination of factors is for the highest Grey relational grade, and in this case that is: 5% filler, normal load of 35 N and sliding speed 120 min-1. Further using ANOVA analysis it can be concluded that the most influential factor is the normal load, then the sliding speed and, finally, the percentage of the filler. In the end, a confirmation test was carried out and Grey relational grade increased from the initial combination of factors to an optimal of 72.56% [6]. Taguchi-Grey analysis for the optimization of thermal characteristics (thermal fall / barrier and thermal fatigue cycle) was applied by M. Yunus et al. by considering influencing factors such as: coating thickness, coating type, bond coating and exposure temperature of the coating. Grey relational analysis is done for the quality characteristic lower-the-better and Grey relational grade is obtained. ANOVA analysis of Grey relational grade determined the optimal combination of influence factors, which in this case is for the Super-Z coating type, the exposure temperature of the coating 900° C, the thickness of the coating 300 μm and the bond of the coating 75μm. The greatest influence on thermal characteristics has a type of coating with 72.98% of influence in compared to other factors [7].

The aim of this paper is to obtain an optimal combination of influencing factors in order to achieve the highest values of the efficiency and the output power. Using the Taguchi orthogonal matrix, tests are carried out on the worm gear with different combinations of factors (input number of revolutions, viscosity of the lubricant and current intensity on the control unit) and their levels. On the basis of the obtained experimental results, optimization of the worm gear is performed using the optimization method, in this case the Taguchi method. However, due to problems with multiple outputs, Grey analysis is first approached, and then using the Taguchi method, the most influential factors and the optimal combination of factors are obtained.

2. EXPERIMENT DESIGN

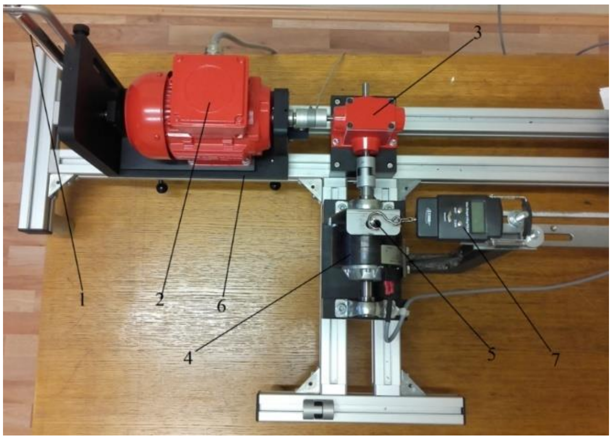
Using the standard orthogonal series, an experiment plan has been formulated. In this paper, the design of the experiment is mainly used to observe the influence of control factors on the output power and the efficiency of the worm gear reducer.

Based on the requirement that the degree of freedom of the orthogonal field is greater than or equal to the sum of the efficiency and power at the output, the standard orthogonal matrix L27 is selected. The considered factors are: the input number of revolutions, the viscosity of the lubricant and current intensity on the control unit, and all factors are the third level. Table 1 shows the control factors with their considered levels.

Table 1. Levels of control factors

Control factors	Unit	Level I	Level II	Level III
(A) Number of revolutions	[min^{-1}]	1500	1750	2000
(B) Viscosity of lubricant	[mm^2/s]	220	460	680
(C) Current intensity	[A]	0.10	0.15	0.20

Worm gear was tested on the AT 200 device shown in Figure 2 a). The AT200 is used for determining the efficiency of gears, the basic parts of the device are: 1-dynamometer at the input, 2-motor, 3-worm gear reducer, 4-brake, 5-brake lever, 6-chassis and 7-dynamometer at the output. This device is connected to the control unit (Figure 2b) at which the input number of revolutions is regulated, that is the number of revolutions of the shaft of the motor, as well as the braking force of the brake that is regulated also on the control unit [8].



a)

b)

Fig. 2. a) device AT 200, b) control unit [8]

Based on the Table 1, the testing of the efficiency and the output power for three input number of revolutions (1500, 1750 and 2000 min^{-1}), three types of viscosity of the lubricants (220, 460, 600 mm^2/s) and three power levels on the brake (0.1, 0.15 and 0.2 A) was carried out.

2.1 Grey analysis

In this paper, it is necessary to optimize the influencing factors, such as the viscosity of the lubricant, the current intensity on the control unit and the input number of revolutions, in order to increase the output power and efficiency of the worm gear reducer. Grey analysis is used in case of optimization when there are multiple outputs. The larger S/N ratio of one characteristic corresponds to the lower S/N ratio of the other, so for the optimization of multiple outputs it is necessary to observe the total S/N ratio. Grey analysis is an efficient optimization tool when there are multiple outputs [9, 10].

Based on the obtained results, Grey analysis is accessed. At the beginning of the Grey analysis, it is necessary to normalize the experimental data. Normalization is the translation of the obtained values into an interval from 0 to 1. For the desired higher values of the efficiency and the power at the output (the criterion higher-the-better) the normalization is done based on the following expression [7]:

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)}, \quad (1)$$

where: *k* represents the number of factors, *i* is the number of the experiment, $\max y_i(k)$ is the largest experimental value for *k*-th output, and $\min y_i(k)$ is the lowest experimental value for *k* -th output [6].

Next, with the help of obtained normalized values, Grey relational coefficient needs to be determined. First value of absolute difference is calculated according to the expression [6]:

$$\Delta_{0i} = \left\| x_0(k) - x_i(k) \right\|, \quad (2)$$

where: $x_0(k)$ referential normalized value ($x_0(k)$ = 1).

After obtaining the values of absolute difference, the Grey relational coefficient is calculated according to [6, 7]:

$$\xi_i(k) = \frac{\Delta_{\min} + \varsigma \Delta_{\max}}{\Delta_{0i}(k) + \varsigma \Delta_{\max}}, \quad (3)$$

where: $\Delta_{\min}$ and $\Delta_{\max}$ the smallest and greatest value of absolute difference, is the distinguishing coefficient in the interval $0 \le \varsigma \le 1$, if the weightage of output is equal, then $\varsigma = 0.5$ [6].

After calculating the Grey relational coefficients, Grey relational grade (γ_i) can be calculated. This grade is calculated according to expression (4) and it needs to be as large as possible [6, 7, 10, 11]:

$$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i, \quad (4)$$

where n is the number of outputs.

In this way, multiple output problems are converted to a single output problem. For further optimization ANOVA analysis was used.

2.2 ANOVA analisys

Taguchi method is an experimental design technique that reduces the number of experimental tests by using orthogonal arrays. The statistical method-Taguchi, using the ANOVA analysis, enables the study of the effects of many factors on the desired output.

In ANOVA analysis, it is necessary to take into account the choice of quality characteristics. Taguchi method uses the method of calculating the S/N ration in dependence on the performance of the experiment, whereby the quality characteristics can be: lower-the-better, higher-the-better, or nominal-the-better. The aim of the paper is to obtain as much efficiency and output power as possible, so ANOVA's analysis of the Grey relational grade is accessed and S/N ratio for the quality characteristic higher-the-better is calculated according to the expression [6]:

$$\frac{S}{N}ratio = -10\log_{10}\left(\frac{1}{n}\cdot\frac{1}{y^2}\right), \tag{5}$$

where *y* Grey is a relational grade, and *n* is the number of repetitions of the experiment.

ANOVA analysis is a statistical method used to predict the most influential factors, and was carried out in the Minitab 16 software [12-17].

3. RESULTS AND DISCUSSION

Table 2 gives input and output values, normalized output values, Grey coefficients, Grey relational grade, and S/N ratio. What can be seen from Table 2 is that for the highest value of Grey relational grades there is the highest S/N ratio.

Table 2. Normalized values, Grey relational coefficients and Grey relational grade

No. exp.	Num.of revol. [min^{-1}]	Viscosity of lubric. [mm^2/s]	Current intensity [A]	Output power [W]	Efficiency	Grey koef. (output power)	Grey koef. (efficiency)	Grey relation grade	S/N ration (Grey relation grade)	Rank
1	1500	220	0.1	21.74	0.55372	0.3387	0.3362	0.3375	-9.4355	27
2	1500	220	0.15	37.00	0.620429	0.4309	0.4904	0.4606	-6.7326	19
3	1500	220	0.2	51.37	0.646171	0.5794	0.5959	0.5876	-4.6178	13
4	1500	460	0.1	20.59	0.564106	0.3333	0.3535	0.3434	-9.2834	25
5	1500	460	0.15	37.25	0.633007	0.4328	0.5368	0.4848	-6.2883	18
6	1500	460	0.2	51.91	0.671985	0.5871	0.7597	0.6734	-3.4349	9
7	1500	680	0.1	23.01	0.551893	0.3449	0.3333	0.3391	-9.3937	26
8	1500	680	0.15	39.35	0.642299	0.4497	0.5772	0.5135	-5.7898	17
9	1500	680	0.2	53.07	0.682515	0.6041	0.8557	0.7299	-2.7352	6
10	1750	220	0.1	23.00	0.564304	0.3448	0.3539	0.3493	-9.1355	24
11	1750	220	0.15	44.50	0.639002	0.4975	0.5622	0.5298	-5.5172	16
12	1750	220	0.2	61.40	0.663435	0.7631	0.6963	0.7297	-2.7374	8
13	1750	460	0.1	53.07	0.682515	0.6041	0.8557	0.7299	-2.73515	6
14	1750	460	0.15	46.99	0.651463	0.5243	0.6234	0.5739	-4.8235	14
15	1750	460	0.2	61.36	0.683363	0.7622	0.8644	0.8133	-1.79449	5
16	1750	680	0.1	27.11	0.576258	0.3663	0.3762	0.3712	-8.6071	22
17	1750	680	0.15	47.99	0.661694	0.5360	0.6846	0.6103	-4.2885	11
18	1750	680	0.2	63.64	0.694548	0.8213	1.0000	0.9106	-0.8131	2
19	2000	220	0.1	30.93	0.583913	0.3888	0.3920	0.3904	-8.1701	20
20	2000	220	0.15	48.23	0.642289	0.5389	0.5771	0.5580	-5.0667	15
21	2000	220	0.2	68.31	0.669044	0.9763	0.7366	0.8564	-1.3460	4
22	2000	460	0.1	28.95	0.567524	0.3768	0.3596	0.3682	-8.6785	23
23	2000	460	0.15	49.11	0.657316	0.5497	0.6570	0.6034	-4.3881	12
24	2000	460	0.2	68.90	0.688926	1.0000	0.9269	0.9635	-0.3232	1
25	2000	680	0.1	31.99	0.57582	0.3956	0.3753	0.3854	-8.28107	21
26	2000	680	0.15	51.58	0.66329	0.5824	0.6953	0.6389	-3.8919	10
27	2000	680	0.2	61.62	0.692251	0.7684	0.9688	0.8686	-1.22351	3

Table 3 gives a response for the Grey relational grade, or the mean S/N ratio for each level of control factors. The response table also shows ranking of the influential factors, based on delta values (difference between maximum and minimum).

Table 3. Responses for Grey relation grade

Level	A	B	C
1	0.4966	0.5333	0.4016
2	0.6242	0.6171*	0.5526
3	0.6259*	0.5964	0.7926*
Delta	0.1292	0.0838	0.3910
Rank	2	3	1

The factor with the highest delta value is ranked first, the factor with the second largest delta value as the second, and the least impact factor is ranked as the third. In this case, the factor with the highest delta value is the current intensity on the control unit.

Figure 3 shows the influence of the current intensity on the control unit, the input number of velocity and the viscosity of the lubricant in relation to the mean value of S/N ratio. Based on the graphics, it is possible to determine the optimal combination of factors to the observed output values. The most optimal combination of factors for the efficiency and output power is A3B2C3, that is, the number of revolutions 2000 min^{-1}, the viscosity of the lubricant 460 mm^2/s and the current intensity of 0.2 A.

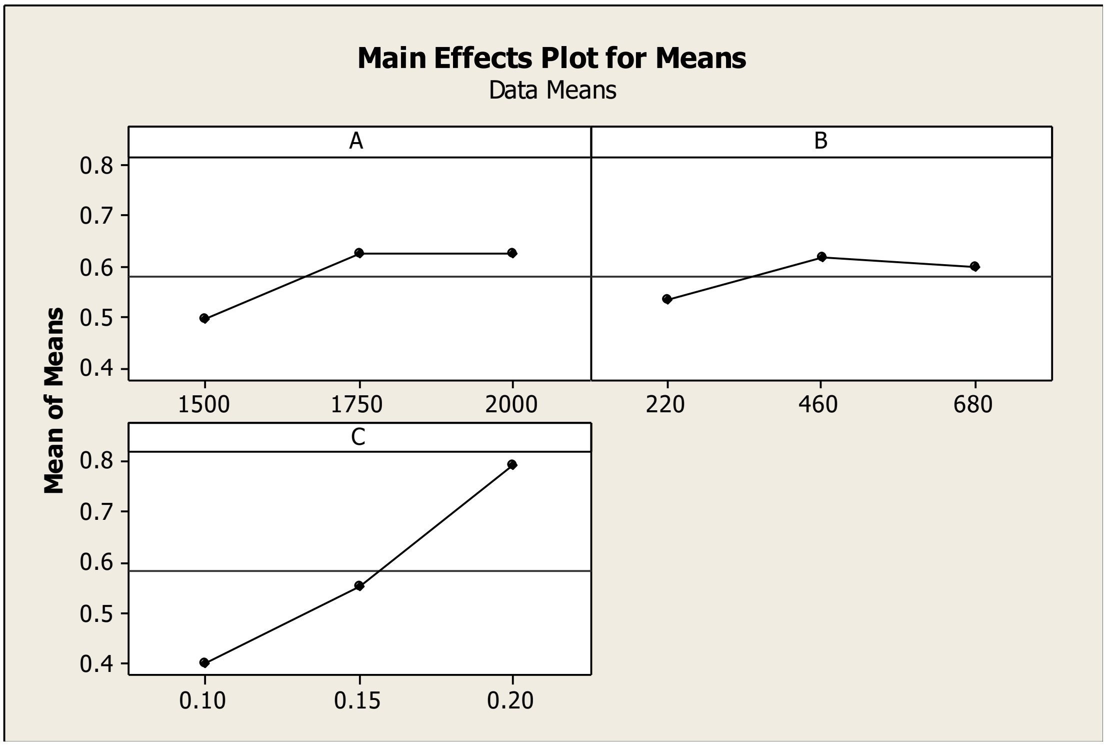


Fig 3. Impact graphics for mean value of Grey relation grade

ANOVA analysis was performed for a level of significance of 5% and for a confidence level of 95%. The level of significance indicates the reliability of the replication of the experimental results; for a level of significance of 5%, the results are similar to the experimental results. P value given in Table 4 indicates the level of factor influence, and is 0.05 for a level of significance of 5%. When the P value is less than 0.05, the corresponding factor has a greater influence on the Grey relational grade. In the last column of Table 4, the percentage impact of the factor on the Grey relational grade is given.

Based on Fischer's distribution by 95% (F= 4.459), observing Table 4, it is noticed that, except influence of the most significant factor C (current intensity on the control unit) with 72.1%, there is influence of factor A (input number of velocity) with 10.2%. The influence of factor B (viscosity of lubricants) and interaction of factor can be neglected on the influence of the output power and the efficiency of the worm gear reducer.

Table 4. Results of ANOVA analysis for Grey relational grade

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Pr. %
A	2	0.09895	0.09895	0.049473	6.87	0.018	10.2
B	2	0.03431	0.03431	0.017155	2.38	0.154	3.5
C	2	0.69971	0.69971	0.349853	48.62	0.000	72.1
A*B	4	0.01839	0.01839	0.004598	0.64	0.649	1.9
A*C	4	0.03879	0.03879	0.009698	1.35	0.333	4.0
B*C	4	0.02278	0.02278	0.005695	0.79	0.562	2.3
Residual error	8	0.05757	0.05757	0.007196			5.9
Total	26	0.97050					100

4. CONCLUSION

The application of Taguchi-Grey analysis on the problem with multiple outputs is shown in this paper. The influence of the viscosity of the lubricant, the current intensity on the control unit and the input number of velocity, on the efficiency and power at the output were considered. Based on the conducted Taguchi-Grey analysis, the following can be concluded: from Table 2 it can be noted that the highest Grey relational grade for the 24th experiment and the factors: Number of revolutions 2000 mm^2/s, viscosity of lubricant 460 mm^2/s and current intensity 0.2 A. For this factor combination Grey relational grade is 0.9635.

Using the ANOVA analysis can be concluded that on the output power and the efficiency of worm gear the greatest influence have the current intensity on the control unit with 72.1%, followed by the number of revolutions with 10.2%. The influence of the viscosity of the lubrication as well as the influence of the interaction factor on the output values can be ignored.

This analysis enables the achievement of the maximum value of efficiency of the worm gear reducer, which also enables the determination of an optimal combination of factors with the least losses in the worm gear reducer and with the highest output power.

Based on experimental results and using the Taguchi method and Grey analysis, it has been concluded that these methods are applicable for optimizing the efficiency and output power of worm gear.

ACKNOWLEDGEMENT

This paper presents the results obtained during research within the framework of the project TR 35021, supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia.

REFERENCES

[1.] V. Nikolić, Machine elements, Faculty of Mechanical Engineering, Kragujevac, 2004.

[2.] A. Skulić, D. Krsmanović, S. Radosavljević, L. Ivanović, B. Stojanović, Power losses of worm gear pairs, Acta Technica Corviniensis – Bulletin of Engineering, 10(3), 2017:39-45.

[3.] M. Turci, E. Ferramola, F. Bisanti, G. Giacomozzi, Worm Gear Efficiency Estimation and Optimization, Gear Techn, 33 (4), 2016: 46-53.

[4.] B. Magyar, B. Sauer, Calculation of the Efficiency of Worm Gear Drives, Power Transmission Engineering, 9 (4), 2015:52-56.

[5.] H. Siebert, Worm Gears-Higher Energy Efficiency and Less Strain on Resources, Gear Techn, 28 (3), 2011:26-30.

[6.] J. Sudeepana, K. Kumarb, T.K. Barmanc, P. Sahooc, Study of tribological behavior of ABS/ CaCO3 composite using Grey relational analysis, , Proc Mater Sci 6 (2014) pp.682 – 691.

[7.] M. Yunus, M.S. Alsoufi, S.M. Munshi, Taguchi-Grey relation analysis for assessing the optimal set of control factors of thermal barrier coatings for high-temperature applications, Mech Adv Mater Struc, 2(4), 2016:1-8.

[8.] B. Stojanović, S. Radosavljević, S. Veličković, S. Miladinović, M. Bukvić, The influence of lubricant viscosity on the efficiency of worm gear reducer, 8th International Scientific Conference Research and development of mechanical elements and systems (IRMES 2017), 7-9 Septembar, 2017, Trebinje, Bosna I Hercegovina, 2017, pp. 219-225.

[9.] J. Deng, Introduction to Grey system theory, J Grey Syst , 1 (1), 1989:1–24.

[10.] S. Ghosh, P. Sahoo, G. Sutradhar, Tribological Performance Optimization of Al-7.5% SiCp Composites Using the Taguchi Method and Grey Relational Analysis, J. Compos., 2013, 2013, 1-9.

[11.] V.R. Ramakoteswara, N. Ramanaiah, M.M.M. Sarcar, Ch. R. Deva, Application of Grey-Taguchi Technique for Optimization of Process Parameters for Wear Behaviour on AA7075-TiC Metal Matrix Composites, 6th International & 27th All India Manufacturing Technology 2016, Design and Research (AIMTDR 2016) 16-18 December, 2016, Pune, India, pp. 1685-1688.

[12.] L. Ivanović, B. Stojanović, J. Blagojević, G. Bogdanović, A. Marinković, Analysis of the flow rate and the volumetric efficiency of the trochoidal pump by application of Taguchi method, Tech. Gazz., 24, Suppl. 2, 2017: 265-270.

[13.] S. Veličković, B. Stojanović, M. Babić, I. Bobić, Optimization of tribological properties of aluminum hybrid composites using Taguchi design, J. Compos. Mater., 51 (17), 2017: 2505 – 2515.

[14.] B. Stojanović, M. Babić, S. Veličković, J. Blagojević, Tribological behavior of aluminum hybrid composites studied by application of factorial techniques, Tribol. Trans., 59 (3), 2016: 522-529.

[15.] S. Miladinović, S. Veličković, M. Novaković, Application of Taguchi method for the selection of optimal parameters of planetary driving gear, Appl. Eng. Lett., 1 (4), 2016: 98-104.

[16.] B.Stojanović, J. Blagojević, M.Babić, S.Veličković, S.Miladinović, Optimization of hybrid aluminum composites wear using Taguchi method and artificial neural network, Ind. Lubr. Tribol., 69(6), 2017, https://doi.org/10.1108/ILT-02-2017-0043.

[17.] B. Stojanović, M. Babić, L. Ivanović, Taguchi optimization of tribological properties of Al/SiC/Graphite composite; J.Balk. Tribol. Assoc., 22(3), 2016: pp.2592-2605