The Influence of Lubrication on the Roughness of the Vibroburnished Surface

Gheorghe Nagîț[1[0000-0001-9649-8525]], Laurențiu Slătineanu[1[0000-0002-5976-9813]], Oana Dodun[1[0000-0003-4047-3550]], Viorel Păunoiu[2[0000-0001-7846-4102]], Marius-Andrei Mihalache[1[0000-0002-9078-785X]], Marius-Ionuț Rîpanu[1], Adelina Hrițuc[1*] [0000-0003-3871-7800] , Ioan Surugłu

[1] "Gheorghe Asachi" Technical University of Iași, Blvd. D. Mangeron, 39, Iași 700050, România
[2]"Dunărea de Jos" University of Galați, Str. Domnească 47, România
*adelina.hrituc@student.tuiasi.ro

Abstract. One of the processes by which hardening of the surface layer and diminishing the heights of the surface roughness occur in the case of steel parts is vibroburnishing. The analysis of the conditions of using the vibroburnishing process of the cylindrical surfaces showed that the use of lubrication could influence the heights of the asperities resulting from the processing. The problem of conducting experimental research was formulated to highlight the intensity of the influence exerted by some input factors in the vibroburnishing process on the roughness of the processed surfaces, evaluated by using the roughness parameter *Ra*. An experimental program was designed aiming to use different values of ball diameter, ball pressing force, and initial roughness, in conditions of dry vibroburnishing and using lubricating oil, respectively. The experimental results were processed using a software based on the least-squares method. The determined empirical mathematical models showed that, under the conditions in which the experimental tests were performed, the strongest influence on the value of the roughness parameter *Ra* is exerted by the initial surface roughness, followed by the size of the ball pressing force on the surface and by the ball diameter, the latter exerting very little influence. It was confirmed that the presence of a lubricant in the processing area results in a decrease in the size of the roughness parameter *Ra*, compared to the situation where such a lubricant is not used.

Keywords: Vibroburnishing, Lubrication Influence, Surface Roughness, Empirical Mathematical Model.

1 Introduction

When relatively low values of roughness parameters are prescribed in the mechanical drawings of metal parts, it is necessary to apply smoothing procedures, which reduce the heights of the roughness generated by previous processing. Processes that can

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (http://creativecommons.org/licenses/by/4.0/).

be used to reduce the height of the roughness of a surface belonging to a workpiece metal material may be based on a removal of the material or plastic deformation of the roughness. Among the procedures included in the last category, it can mention burnishing with a ball, roller, or with fixed tips made of hard materials and having a certain radius of rounding of the tips of partially hemispherical shape, vibroburnishing in conditions similar to those mentioned for the case of burnishing, etc.

In the case of burnishing, a ball or roller can be used, pressed with a certain force, and rolled over the entire surface of the workpiece to be finished due to a certain processing scheme. For example, in the case of cylindrical surfaces, it is necessary to combine a rotational movement of the workpiece with a longitudinal feed movement of the ball or roller pressed on the cylindrical surface of the workpiece. There is also a variant of burnishing in which, instead of the ball, a conical piece of hard material is used and whose tip has a partially hemispherical surface. In this case, it is no longer dealing with a rolling motion of a boll or cylindrical roller on the surface of the workpiece, and the plastic deformation of the surface layer occurs as a result of the direct action of the active area of the tip made of the hard material (which can be, for example, diamond) on the roughness of the surface of the workpiece on which the hard tip is pressed and moved.

In the case of vibroburnishing, concerning those mentioned above, a vibratory movement of the tool is used, usually along a direction perpendicular to that of the direction of action of the pressing force, possibly correlated with the other movements, for the entire surface to be finished.

The arithmetic deviation *Ra* of the assessed profile and, relatively rarely, the total height *Rz* of the asperities on the assessed profile are currently mainly used as parameters for characterizing the surface roughness.

The reduction of roughness heights by vibroburnishing has been a concern of researchers in manufacturing engineering, and the results of their theoretical and experimental research on this subject have been published.

Thus, the first approaches to some aspects of vibroburnishing processes seem to have been taken by Schneider and Ryzhov. In 1972, they published papers describing aspects related to the processes in the contact area between the tool and the workpiece material in the case of vibroburnishing [1-3].

Aspects regarding the height of the roughness generated by vibroburnishing processes have been addressed in more extensive works since the 1980s [4, 5].

In an article published in 1990, Barski presented the results of research on the influence of some of the working conditions on the sizes of some output parameters of the vibratory burnishing process [6]. These output parameters included surface roughness. An empirical mathematical model in the form of a second-degree polynomial was proposed to highlight the influence of different factors on the variation of the value of the roughness parameter *Ra*. Patel and Patel investigated the influence of the workpiece rotational speed, the feed rate, the size of the pressing force, and the vibrating motion's frequency on the size of the roughness parameter *Ra*, using the response surface method [7]. They also determined a second-degree polynomial-type mathematical model by mathematically processing the experimental results.

Slavov et al. conducted experimental research on the vibro-burnishing ball process on a multi-axis CNC milling center. They showed that when using a Mobil DTE 25 type lubricant, it is possible to reduce the roughness parameter Rz's value to 4.2 μm [8].

In the present paper, the research results on the influence of factors specific to the vibroburnishing process, including the presence or absence of a lubricant, on the value of the roughness parameter *Ra* are presented. A first presentation of the theoretical conditions in which the vibroburnishing process was carried out using balls, with or without lubrication. Next, the conditions for conducting experimental research were presented, respectively the experimental results obtained and some empirical mathematical models determined by processing the experimental results using specialized software.

2 Basic processes for finishing surfaces by vibroburnishing with and without lubrication.

A schematic representation of a vibroburnishing process of an outer cylindrical surface can be seen in Figure 1. A ball made of hard material is pressed against the surface of the workpiece with a force *F* large enough to produce plastic deformation of the roughness and a redistribution of the material at the level of the workpiece surface layer. The workpiece will perform an n_W rotational motion, while the burnishing tool will perform a longitudinal feed motion f_T to traverse the surface required to be vibroburnished. As the machining scheme corresponds to a vibroburnishing process, a v_m vibration movement, also performed by the burnishing tool, with known amplitude and frequency, was considered.

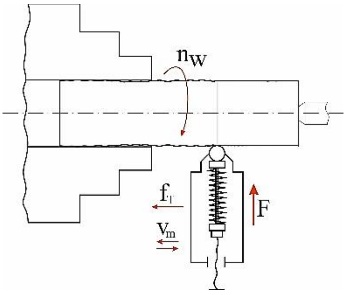

Fig. 1. Schematic representation of the vibroburnishing process of an outer cylindrical surface**.**

The schematic representation in Figure 2 illustrates the ball's rolling on the surface of the workpiece and the plastic deformation of the roughness. The existence of an initial surface profile of the workpiece with a certain level of regularity was taken into account, such as, for example, the profile of an area resulting from longitudinal turning with a constant feed rate. In this way, at the micro space level, the roughness peaks go down, the bottoms of the gaps rise, and the new roughness has a wider width than the initial ones.

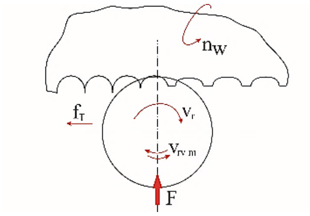

Fig. 2. Deformation of roughness during dry vibroburnishing.

Under the action of the feed movement and the intense friction between the ball and the workpiece surface, the ball will make a rolling motion v_r. As the ball support subsystem is additionally engaged in a rectilinear vibratory motion, this will lead to the overlapping, in addition to the above-mentioned rolling motion, of an additional rolling motion in both directions as a result of the vibratory motion. This last rolling motion amplifies the plastic deformation effects of the roughness generated by the first rolling motion. The presence of lubricant (Fig. 3) will reduce the possible adhesion effects between the ball material and the workpiece material, resulting in the possibility of an additional decrease in the heights of the roughness on the vibroburnished surface.

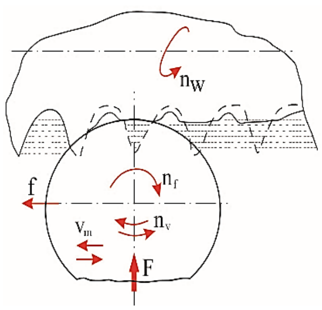

Fig. 3. Detail of the vibroburnishing area in the presence of a lubricant

3 Experimental conditions

Through experimental research it was proposed to highlight the order of influence and the intensity of the influence of some of the factors capable of affecting the values of the roughness parameter *Ra*, as a result of applying the vibroburnishing process with and without lubrication, respectively. The aim was to determine some empirical mathematical models obtained by mathematical processing of experimental results.

There are many factors and groups of factors capable of influencing the values of the roughness parameter *Ra* when applying the vibroburnishing process. Thus, it can consider the nature and some physical-mechanical properties of the workpiece material, the size of the ball radius used as a burnishing tool, the force of the ball pressing on the surface of the workpiece, the specific values of processing conditions (peripheral speed of the workpiece, feed rate) vibratory movement (frequency and amplitude), the height of the roughness obtained by the previous processing, the presence or absence of lubricant in the working area, etc. Taking into account the available conditions, the diameter d_b of the ball (two distinct values, 6.75 mm and 11.32 mm), the size of the force exerted on the ball (20 distinct values, between 65 and 670 N), 4 values of the initial roughness of the surface to be vibroburnished (Ra = 1.05 μm, 1.67 μm, 3.25 μm and 5.32 μm) were selected as input factors). Using these values, two sets of experimental tests were performed, with and without the use of a lubricant (H20, in accordance with the Romanian standard STAS 9691-74). The vibratory motion was characterized by an amplitude of 1.6 mm and a frequency of 6.1 Hz. Bushings with an inner diameter of 20 mm, the length of 30 mm, and an outer diameter of 75.1 mm were used as test samples. The material from which the test samples were made was steel 1.0060 (having a hardness of 220 HV). The test samples were located and clamped on a mandrel. The mandrel was located and clamped at the left end in a universal chuck, and at the right end in a rotating live center. Experimental tests were performed on a universal lathe type SN 400x1000 (made in Romania).

A device was used to ensure conditions for supporting, pressing and moving the ball on the surface of the workpiece. This device has been mounted using the universal lathe tool holder [9-11]. The experimental tests were performed in dry conditions, i.e., without the use of a lubricant and respectively in the presence of a lubricant (oil H20), brought to the drip processing area [11].Roughness parameter values were determined using a roughness meter type G4 (manufactured in the former Soviet Union).The experimental tests were performed using the processing scheme in Figure 1. The values of the parameters that characterize the test conditions and the results obtained are listed in Table 1.

4 Experimental results

The mathematical processing of the experimental results listed in Table 1 was performed using specialized software based on the least-squares method [12]. This software allows the selection of the most appropriate empirical mathematical model from five such models available (first-degree polynomial, second-degree polynomial, power-type function, exponential function, hyperbolic function).

The most appropriate empirical mathematical model was selected using the value of Gauss's criterion.

The value of the Gauss's criterion is calculated as a sum of the squares of the differences in the ordinates of the experimentally determined points and the points corresponding to a certain mathematical model. The lower the value of Gauss's criterion, the more appropriate the determined mathematical model is to the experimental results.

The most appropriate empirical mathematical models can be determined in this way by taking into account the experimental results. When such an empirical mathematical model determined to be the most appropriate in relation to the experimental results is in the form of a second-degree polynomial, for example, simply examining the coefficients corresponding to the terms of the polynomial does not provide sufficient information on the order of factors and the intensity of their influence on the value of the roughness parameter *Ra*.

Table 1. Test conditions and experimental results.

Ball diameter, d_b, mm	Force, F, N	Surface roughness parameter *Ra* of the initial surface							
		Ra_{in}=1.05 µm		Ra_{in}=1.67 µm		Ra_{in}=3.25 µm		Ra_{in}=5.32µm	
		With lubrication	Without lubrication	With lubrication	Without lubrication	With lubrication	Without lubrication	With lubrication	Without lubrication
6.75	65	0.95	0.75	1.02	0.82	2.5	2.05	4.22	3.25
6.75	100	0.82	0.615	0.92	0.75	1.75	1.51	3.89	2.98
6.75	135	0.73	0.60	0.81	0.68	1.62	1.43	3.72	2.90
6.75	150	0.68	0.58	0.72	0.61	1.58	1.38	3.65	2.89
6.75	165	0.65	0.53	0.67	0.55	1.50	1.36	3.61	2.76
6.75	180	0.59	0.50	0.59	0.51	1.45	1.30	3.52	2.71
6.75	200	0.49	0.445	0.53	0.42	1.33	1.25	3.45	2.73
6.75	235	0.46	0.415	0.50	0.43	1.30	1.17	3.41	2.60
6.75	265	0.424	0.405	0.48	0.40	1.25	1.08	3.32	2.51
6.75	300	0.405	0.39	0.44	0.39	1.20	0.95	3.25	2.46
6.75	340	0.4	0.38	0.42	0.385	1.18	0.91	3.20	2.42
6.75	370	0.39	0.375	0.405	0.38	1.15	0.85	3.17	2.37
6.75	400	0.395	0.37	0.40	0.375	1.12	0.84	3.05	2.32
6.75	435	0.4	0.37	0.41	0.38	1.10	0.83	3.02	2.28
6.75	460	0.41	0.375	0.43	0.39	1.10	0.82	3.00	2.25
6.75	500	0.42	0.38	0.435	0.395	1.12	0.85	3.04	2.23
6.75	535	0.435	0.39	0.45	0.41	1.21	0.87	3.07	2.21
6.75	565	0.445	0.395	0.47	0.425	1.25	0.89	3.11	2.22
6.75	600	0.51	0.4	0.483	0.43	1.26	0.92	3.15	2.26
6.75	635	0.52	0.41	0.51	0.44	1.29	0.98	3.25	2.29
6.75	670	0.535	0.42	0.54	0.445	1.31	0.99	3.26	2.37
11.32	65	0.9	0.7	0.94	0.74	2.35	1.94	4.1	3.11
11.32	100	0.8	0.52	0.81	0.65	2.05	1.81	3.8	2.8
11.32	135	0.7	0.46	0.72	0.59	1.85	1.72	3.55	2.7
11.32	150	0.6	0.43	0.67	0.52	1.82	1.66	3.45	2.61
11.32	165	0.52	0.38	0.64	0.50	1.80	1.61	3.37	2.52
11.32	180	0.48	0.37	0.58	0.46	1.76	1.55	3.30	2.43
11.32	200	0.43	0.36	0.48	0.43	1.72	1.51	3.24	2.34
11.32	235	0.41	0.33	0.425	0.46	1.68	1.48	3.19	2.25
11.32	265	0.38	0.31	0.41	0.39	1.65	1.46	3.15	2.16
11.32	300	0.365	0.305	0.4	0.385	1.64	1.45	3.12	2.07
11.32	340	0.33	0.29	0.39	0.37	1.60	1.44	3.10	2.00
11.32	370	0.32	0.28	0.38	0.36	1.52	1.43	3.09	1.96
11.32	400	0.31	0.28	0.37	0.36	1.48	1.435	3.08	1.97
11.32	435	0.32	0.285	0.38	0.365	1.46	1.44	3.09	1.98
11.32	460	0.33	0.29	0.4	0.37	1.47	1.445	3.09	2.02
11.32	500	0.335	0.30	0.41	0.375	1.48	1.45	3.1	2.04
11.32	535	0.34	0.31	0.425	0.38	1.49	1.45	3.11	2.05

11.32	565	0.35	0.315	0.435	0.39	1.61	1.46	3.12	2.06
11.32	600	0.36	0.32	0.50	0.40	1.61	1.47	3.13	2.07
11.32	635	0.37	0.33	0.51	0.405	1.62	1.47	3.14	2.09
11.32	670	0.38	0.35	0.53	0.41	1.62	1.48	3.14	2.1

On the other hand, in manufacturing engineering, the use of power-type functions as empirical mathematical models is frequently preferred, as the values of the exponents attached to the independent variables in the mathematical relation clearly highlight the order of influence of the factors and their influence intensity. Such empirical mathematical models of power-type function type are used, for example, to highlight the influence exerted by different factors on the cutting tool life, on the values of some parameters of surface roughness, on the size of the cutting forces, etc.

The most appropriate empirical mathematical models can be determined in this way by taking into account the experimental results. When such an empirical mathematical model determined to be the most appropriate in relation to the experimental results is in the form of a second-degree polynomial, for example, simply examining the coefficients corresponding to the terms of the polynomial does not provide sufficient information on the order of factors and the intensity of their influence on the value of the roughness parameter *Ra*. On the other hand, in manufacturing engineering, the use of power-type functions as empirical mathematical models is frequently preferred, as the values of the exponents attached to the independent variables in the mathematical relation clearly highlight the order of influence of the factors and their influence intensity. Such empirical mathematical models of power-type function type are used, for example, to highlight the influence exerted by different factors on the cutting tool life, on the values of some parameters of surface roughness, on the size of the cutting forces, etc.

Under the above conditions, the following empirical mathematical models have been determined:

1. In the case of vibroburnishing without lubrication:

a) The most appropriate mathematical model is in the form of a polynomial of the second-degree:

$$Ra=1.364-0.169d_b+0.0093d_b^2-0.00342F+0.00000368F^2+0.264Rai+0.0342Rai^2, \quad (1)$$

for which the value of the Gauss's criterion is $S_G = 0.03922339$;

b) The empirical mathematical model corresponding to the power type-function:

$$Ra=1.339d_b^{-0.0554}F^{-0.236}Rai^{1.175}, \quad (2)$$

the value of Gauss's criterion being $S_G = 0.04226187$.

2. In the case of lubricated vibroburnishing:

a) The most appropriate empirical mathematical model is also a second-degree polynomial:

$$Ra=1.318-0.0690d_b+0.00399d_b^2-0.00432F+0.00000485F^2+0.270Rai+0.101Rai^2, \quad (3)$$

the value of Gauss's criterion being $S_G = 0.02753546$.

b) Mathematical model of power-type function:

$$Ra=1.590d_b^{-0.0492}F^{-0.248}Rai^{1.269}, \quad (4)$$

the value of Gauss's criterion being $S_G = 0.0859328$

Taking into account the mathematical models of the power function type, the graphical representations in Figures 4, 5 and 6 have been performed.

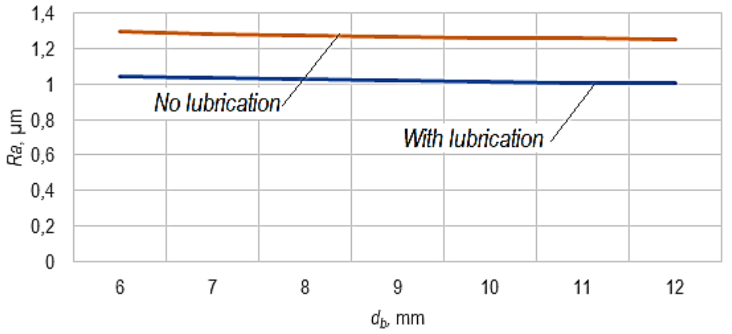

Fig. 4. Influence of ball diameter d_b on *Ra* roughness size obtained after vibroburnishing application (F = 670 N, Rai = 3.25 µm).

In the case of both vibroburnishing without lubrication and with lubrication, the factor that exerts the greatest influence is the value of the *Rai* roughness parameter corresponding to the surface before the application of the vibroburnishing process. Indeed, in the empirical mathematical models constituted by equations (2) and (4), the highest absolute values of the exponents are those attached to the *Rai* factor.

Taking into account the mathematical models of the power function type, the graphical representations in Figures 4, 5 and 6 have been performed.

In the case of both vibroburnishing without lubrication and with lubrication, the factor that exerts the greatest influence is the value of the *Rai* roughness parameter corresponding to the surface before the application of the vibroburnishing process. Indeed, in the empirical mathematical models constituted by equations (2) and (4), the highest absolute values of the exponents are those attached to the *Rai* factor.

As expected, an increase in the value of the *Rai* roughness parameter corresponding to the initial workpiece surface will lead to a higher increase in the size of the *Ra* roughness parameter corresponding to the surface subjected to vibroburnishing processing.

The magnitude of the force F exerts a significantly lower influence applied to the ball. Its increase contributes to a decrease in the size of the roughness parameter *Ra*, which is underlined by the negative values of the exponents attached to the factor F. A

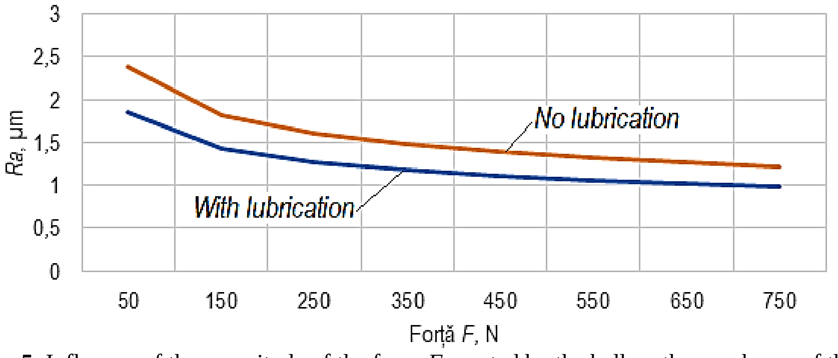

Fig. 5. Influence of the magnitude of the force F exerted by the ball on the roughness of the surface made by burnishing (d_b = 11.32 mm, Rai=3.25 µm).

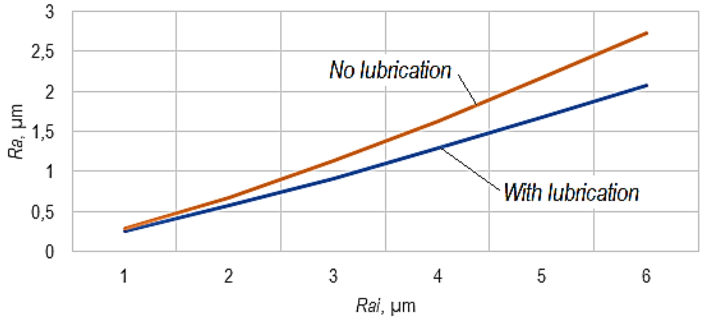

Fig. 6. Influence of the initial roughness size *Rai* on the roughness size *Ra* obtained after vibroburnishing application (F = 670 N, d_b = 11.32 mm).

very small influence seems to be exerted by the diameter of the d_b ball, as the values of the exponents attached to the d_b factor in the empirical mathematical models (2) and (4) are very small and could even be considered negligible.
The graphical representations in Figures 4, 5 and 6 confirm the significant decrease in the value of the roughness parameter *Ra* when using lubrication.

5 Conclusions

The study of the specialized literature regarding the use of the vibroburnishing process highlights the increased interest regarding the better knowledge of the conditions in which, acting on some input factors, it becomes possible to improve the results of technological interest of the process application. This article first used an analysis of the theoretical conditions that could justify the reduction of the heights of the roughness affected by the process to the heights of the roughness before the application of vibroburnishing. Experimental research on the influence exerted by different factors on the size of the roughness parameter *Ra* before and after the application of a vibroburnishing processing was planned and materialized. Through the mathematical processing of the experimental results, empirical mathematical models were determined to provide information on the order of the influencing factors and on the intensity of the influences exerted by the input factors on the values of the roughness parameter *Ra*. It was found that the factor with the greatest influence is the initial roughness of the surface, followed by the size of the force exerted on the ball and the ball diameter, respectively. The reduction of the roughness parameter Ra values when using a lubricant introduced in the drip processing area was confirmed. In the future, it is intended to deepen the theoretical research able to explain how the presence of lubricant contributes to reducing the values of the roughness parameters of the processed surfaces. It is also intended to extend the experimental research for other test sample materials by modifying some parameters that characterize the vibratory motion performed by the ball.

References

1. Schneider, Y.G.: Vibroburnishing of machine elements surface (in Russian). Machine tools and Tools, 3, 34-35 (1972).
2. Ryzhov, E.V., Belov, V.A., Suspov, A.G.: Increasing contact stiffness by vibroburnishing (in Russian). Machine Tools and Tools, 1, 37-38 (1972).
3. Singhal, K.A.: Investigations on the improvement of surface finish and hardness of the work material with burnishing process. Dissertation. University of Roorky (1973).
4. Schneider, Y.G.: The operational properties of parts with regular microrelief (in Russian). 2nd edn. Mashinostroenie, Leningrad (1982).
5. Odintsov, L.G.: Hardening and finishing of parts by surface plastic deformation (in Russian). Mashinostroenie, Moscow (1987).
6. Barski, T., Gajek, M.: Vibratory burnishing of external cylindrical surfaces. In: Conf. Proc.: ICSP-4, pp.119-126. Tokyo (1990).
7. Patel, M.K., Patel, M.D.: Optimization of input process parameters for vibratory ball burnishing process using RSM. International Journal of Research in Engineering & Applied Sciences, 2(2), 372-381 (2012).
8. Slavov, S., Dimitrov, D., Iliev, I.; Variability of regular relief cells formed on complex functional surfaces by simultaneous five-axis ball burnishing. UPB Scientific Bulletin, Series D: Mechanical Engineering, 82(3), 195–206 (2020).
9. Nagîţ, G., Slătineanu, L., Dodun, O., Rîpanu, M. I., Mihalache, A., Boca, M., Hriţuc, A.: Influence of the ball vibrorolling parameters on the surface roughness and on the superficial layer hardness. Materials Science Forum, 957, 130–137 (2019).
10. Nagîţ, G., Slătineanu, L., Dodun, O., Rîpanu, M.I.: Mihalache, A.M. Surface layer microhardness and roughness after applying a vibroburnishing process. Journal of Materials Research and Technology, 8, 4333-4346 (2019).
11. Nagîț, G., Slătineanu, L., Dodun, O., Mihalache, A.M., Rîpanu, M.I., Hriţuc, A.: Influence of some microchanges generated by different processing methods on selected tribological characteristics, Micromachines 13, 29 (2022).
12. Crețu, G.: The basis of experimental research; laboratory handbook (in Romanian). "Gheorghe Asachi" Technical University of Iași, Romania (1992).