Influence of some process input factors on the main dimensions of the grooves generated during the ball vibroburnishing

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Abstract. The ball vibroburnishing is a processing method based on the plastic deformation of the workpiece surface layer, as a result of a vibration movement achieved by the ball pressed with a known force on the workpiece surface. The surface obtained by ball vibroburnishing includes grooves with different directions and partially overlapped. To know better the influence exerted by the ball vibroburnishing conditions on the main dimensional characteristics of the grooves, an experimental research was designed and materialized. As the process input factors, the diameter of the ball, the force, and the workpiece rotation speed were used. The depth and width of the grooves generated by the moving balls on the workpiece surface layer were measured. By mathematical processing of the experimental results, empirical mathematical models were determined. These models highlight the intensity of the influence exerted by the ball vibroburnishing process input factors on the main dimensions of the grooves.

1. Introduction

In the case of steel to which the thermal treatments could not be applied, to improve their functional properties, it is possible to affect surface roughness, and, on the other hand, the properties of the surface layer. With this aim in view, cutting processes and processes based on the plastic deformation of the workpiece surface layer could be used.

As finishing processes applied in the case of the metallic workpieces and when using the material removal from the workpiece, it can take into consideration the tools characterized by the existence of the metallic cutting edges (turning, milling, etc.), and tools based on the use of the abrasive particles (grinding, honing, lapping, superfinishing, etc.). The influence exerted by the process input factors specific to the cutting processes mentioned above was investigated and there is impressive knowledge on this aspect.

The surface roughness and the mechanical properties of the steels for which the thermal treatments could not be applied can be improved by processes based on the plastic deformation of the workpiece superficial layer. The burnishing and vibroburnishing are such processes applied to change the roughness and the hardness of the surface layer of the workpieces that possess flat or revolutions surfaces [1-8].

The burnishing is performed using balls or diamond tips having a certain rounding working surface and whose moving paths are thus established to entirely cover the surface to be processed. At the same time, the deforming tool is pressed on the workpiece surface to be processed.
In the case of the vibroburnishing, an additional vibration motion ensures a more complex movement of the deformation tool on the workpiece surface and grooves characterized by a lower or higher area of the cross-section are generated on the workpiece surface. If these grooves are of low height, it is expected to obtain low values of the surface roughness parameters that take into consideration the height of the surface asperities. It is also possible that the height and width of the grooves also exert influence on other functional properties of the surfaces obtained by vibroburnishing (friction coefficient, wear resistance, the capacity of retaining the oil, etc.).

There is relatively less information concerning the influence exerted by the surface deformation conditions on the dimensions of the grooves generated by vibroburnishing.

Thus, Schneider and Guzok investigated the influence exerted by the groove area on the value of the friction coefficient in the case of applying the vibroburnishing process to the parts of the refrigeration compressors [9]. They appreciated that, in this way, control of the bearing surface and capacity of retaining the oil and finally an increase of the parts working life are possible. Dmitriev et al. approached the problem of changing the feature of structure transformation as a consequence of applying a nanoburnishing process [10]. They presented inclusively aspects concerning the surface profile taking into consideration the model crystal and the proper working conditions at the level of micro space. Matalin and Svinitskaya performed an investigation concerning the submicroscopic microrelief generated by some different finishing processes, one of them being the vibroburnishing [11].

In the previously published works that were accessible to us, the problem of identifying non-linear empirical mathematical models that highlight the influence of working conditions on the channel sizes generated during ball vibroburnishing was not addressed. The objective of the research whose results are presented in this paper was to identify ways of highlighting the influence exerted by some input factors of the plastic deformation process on the width and depth of the grooves generated by the vibroburnishing applied to test pieces that present cylindrical surfaces. The elasticity characteristics of the workpiece material can influence the geometry of the grooves generated by vibroburnishing as the phenomenon of elastic recovery manifests differently for different metallic materials.

![Figure 1. Schematic representation of the vibroburnishing process.](image)
2. Vibroburnishing process

A processing scheme valid in the case of the vibroburnishing applied to cylindrical surfaces when using the lathe as machine tool and working devices adapted to this machine tool is presented in figure 1.

| Line no. 1 | Ball diameter, $d_b$, [mm] | Force $F$, [N] | Test piece diameter, $d$, [mm] | Groove depth, $h$, [$\mu$m] | Groove width, $l_g$, [$\mu$m] |
|------------|---------------------------|---------------|---------------------------|-----------------|-----------------|
| Column no. 1 | 2 | 3 | 4 | 5 | 6 |
| 3 | 6.75 | 100 | 40 | 7 | 35.2 |
| 4 | 6.75 | 100 | 50 | 8.2 | 36.4 |
| 5 | 6.75 | 100 | 60 | 9 | 39.5 |
| 6 | 6.75 | 300 | 40 | 10.3 | 42.4 |
| 7 | 6.75 | 300 | 50 | 12.5 | 51.2 |
| 8 | 6.75 | 300 | 60 | 14.2 | 53.4 |
| 9 | 6.75 | 500 | 40 | 21 | 70.4 |
| 10 | 6.75 | 500 | 50 | 27 | 80.2 |
| 11 | 6.75 | 500 | 60 | 30 | 81.3 |
| 12 | 11.12 | 100 | 40 | 6 | 42.3 |
| 13 | 11.12 | 100 | 50 | 5.6 | 40.4 |
| 14 | 11.12 | 100 | 60 | 8 | 48.3 |
| 15 | 11.12 | 300 | 40 | 10 | 60.4 |
| 16 | 11.12 | 300 | 50 | 12 | 68.5 |
| 17 | 11.12 | 300 | 60 | 14.3 | 71.3 |
| 18 | 11.12 | 500 | 40 | 17 | 83.4 |
| 19 | 11.12 | 500 | 50 | 26 | 90.3 |
| 20 | 11.12 | 500 | 60 | 28 | 92.7 |
| 21 | 15.85 | 100 | 40 | 5.1 | 50.2 |
| 22 | 15.85 | 100 | 50 | 6.8 | 56.4 |
| 23 | 15.85 | 100 | 60 | 7.6 | 60.3 |
| 24 | 15.85 | 300 | 40 | 9 | 70.4 |
| 25 | 15.85 | 300 | 50 | 10.2 | 72.3 |
| 26 | 15.85 | 300 | 60 | 12.1 | 80.1 |
| 27 | 15.85 | 500 | 40 | 17 | 98.3 |
| 28 | 15.85 | 500 | 50 | 19 | 100 |
| 29 | 15.85 | 500 | 60 | 23 | 108 |

Table 1. Experimental conditions and results.

Input factors whose values have been kept constant: rotation speed $n=250$ rev/min, longitudinal feed $f_l=1.5$ mm/rev, frequency of vibration motion $n_d=350$ double strokes/min, amplitude of vibratory motion $2A=2$ mm.

The ball vibroburnishing device was implemented on a medium-size universal lathe [12]. The device had a plate that facilitated its mounting instead of the common tool holder of the universal lathe. An electric motor transmits a rotational motion to the device shaft through a belt drive. The rotating shaft has a disc at one end where a bolt can be moved along a radial direction and fixed in the desired position. A certain value of the eccentricity of the bolt is thus ensured. A value corresponding
to the double value of the eccentricity will be the amplitude of the vibration movement. A cylindrical joint allowed the bolt to drive a connecting rod. At the other end of the connecting rod, there is a spring subsystem for adjusting the size of the force exerted on the ball that will perform the vibroburnishing process. By placing the ball in contact with the cylindrical test piece surface and pressing it with known values using the arc, the value of the pressing force exerted by the ball on the sample surface was ensured. The device was moved in a longitudinal feed movement of preset value by the lathe apron. The bush type test piece was mounted on a mandrel supported at one end in the universal chuck and at the other end in a live center. The rotation of the mandrel on which the test piece was located was ensured from the main shaft of the universal lathe. Changing the wheels of the belt transmission, the change of the mandrel rotation speed was possible. As a deformation tool, a ball of known diameter and made of high hardness steel (bearing steel, 60 HRC) was used.

3. Design of the experimental research
The processing scheme presented in figure 1 was used to develop the experimental research. Cylindrical bushes with different diameters were used as test pieces. The test pieces were made of steel 1.060, whose chemical composition includes 0.6 % C, 0.6 % Si, 0.7 % Mn, 0.04 % P, 0.05 % S (185 Brinell hardness).

Before developing the proper experimental research, a calibration operation was applied to determine the values of the force that corresponds to the different levels of the spring compression.

As deformation process input factors, initially, the ball diameter $d_b$ and the force $F$ were considered. A detailed analysis of the processes developed at the zone of the work micro space showed that the quantity of the material moved as a result of the plastic deformation could be different for different diameters of the test piece and, for this reason, the test piece diameter $d$ (the external diameter of the bush type test piece) was taken into consideration as a third process input factor. The groove depth $h$ and width $l_g$ were considered as the output parameters. The sizes $h$ and $l_g$ were defined as can be seen in the figure 2, a.

![Figure 2](image)

**Figure 2.** Shape and dimensions of the cross-section that correspond to the grooves performed using the vibroburnishing process and three different values for the deformation forces: $a$ – 100 N, $b$ – 300 N, $c$ – 500 N (test piece material: steel 1.060; $n$=250 rev/min, $f_l$=1.5 mm/rev, $f$=250 double strokes/min=5.8 Hz, $2A$=2 mm, $d_b$=11.12 mm; vertical magnification of 2000, horizontal magnification of 20).

Appreciating that a maximum or a minimum of the process output parameters could correspond to certain values of the process input factors, experimental research at three levels of each process input factor was taken into consideration.
Aiming at developing a maximally completed experiment, the decision of developing a full factorial experiment with three process input factors at three levels was established. This means that $3^3=27$ experiments had to be performed.

The values of the depth and height of the groove were measured using surface roughness tester type G4 (made in the former Soviet Union).

The values of the process input factors were mentioned in the columns nos. 2, 3 and 4 from table 1, while the values of the two process output parameters obtained as a consequence of the experimental research were mentioned in the columns nos. 5 and 6. The values of the input factors of the experimental research were established by taking into account the recommendations of other researchers and as a result of conducting preliminary research.

Three proper images that correspond to the groove cross areas obtained for three different values of the applied force $F$ were presented in figure 2, a, b, and c.

![Figure 3](image)

**Figure 3.** Effect of the ball diameter $d_b$ and force $F$ on the depth $h$ and width $l_g$ of the spiral groove generated by vibroburnishing of a test piece made of steel 1.060 (test piece diameter $d=40$ mm).

4. **Experimental results and their analysis**

Using the surface roughness tester G4 and a movement of the probe tip along the test piece axis, the profiles of all the 27 grooves were obtained. Based on the profilograms, the average depth and width of each groove were evaluated.

The experimental results were mathematically processed using specialized software based on the method of least squares [13]. In this way, the following empirical mathematical models of power type were determined:

$$h=0.0186d_b^{0.258}F^{0.692}d^{0.841} \quad (1)$$

and

$$l_g=0.608d_b^{0.429}F^{0.405}d^{0.35} \quad (2)$$

Based on the empirical mathematical models (1) and (2), the diagrams from figures 3, 4 and 5 were developed. Taking into consideration the empirical mathematical relations (1) and (2) and the graphical representations from figures 3, 4 and 5, some remarks could be formulated.
Thus, in the case of the power type function that corresponds to the depth \( h \) of the groove (relation (1)), the increase of the ball diameter \( d_b \) determines a low decrease of the groove depth \( h \), since the value of the exponent attached to this size is subunit and negative. At the same time, the increase of the force \( F \) and test piece diameter \( d \) leads to a low increase of the groove width \( l_g \), since the exponents attached to the two sizes in the relation (1) are subunit and positive. Among the three process input factors, the test piece diameter \( d \) seems to exert the maximum influence, since to this factor the highest value is attached as an exponent.

An explanation of the decrease of the groove depth \( h \) when the ball diameter \( d_b \) increases could be based on the increase of the material resistance to be penetrated by the ball pressed on the test piece surface. The increase in the dimensions of the groove cross-area when the test piece diameter \( d \) increases also could be explained by a better flow of the material when the peripheral speed of the test piece increases, due to the increase in the test piece diameter \( d \).

**Figure 4.** Effect of the ball diameter \( d_b \) and test piece diameter \( d \) on the depth \( h \) and width \( l_g \) of the spiral groove generated by vibroburnishing of a test piece made of steel 1.060 (force \( F=300 \) N).

**Figure 5.** Effect of the force \( F \) and test piece diameter \( d \) on the depth \( h \) and width \( l_g \) of the spiral groove generated by vibroburnishing of a test piece made of steel 1.060 (ball diameter \( d_b=10 \) mm).
It was expected the increase of the groove dimensions when the force $F$ exerted on the burnishing tool increases, due to the higher penetration of the burnishing tool in the test piece material.

In the case of the groove width $l_g$, the increase of each of the independent variables (ball diameter $d_b$, force $F$ and test piece diameter $d$) have, as a result, a low increase of the dependent variable, since all the exponents have positive subunit value. The highest influence is exerted by the ball diameter $d_b$, since the higher value of the exponent is attached to this independent variable in the relation (2). The influences of the force $F$ and test piece diameter $d$ on the depth $h$ and width $l_g$ of the groove have a similar character, as the two empirical mathematical relations show, but the influence is stronger in the case of the groove depth $h$, since the values of the exponents attached to the two sizes in the relation (1) are higher than those existing in the relation (2).

Experimental results can be taken into account in industrial practice, for example when it is necessary to ensure certain values of tribological characteristics for surfaces found in relative motion to each other.

5. Conclusions
The vibroburnishing is a process based on the plastic deformation of the workpiece surface layer using a ball pressed against the workpiece surface and relative motions able to ensure the covering of the entire workpiece surface to be processed. The grooves generated by burnishing ball on the workpiece surface during the vibroburnishing process could be characterized by their depth and width. The analysis of the experimental conditions in which the ball vibroburnishing process develops showed that some process input factors could exert influence on the two dimensions used to characterize the spiral groove generated by the vibroburnishing process. Experimental research aiming at determining the influence exerted by the ball diameter $d_b$, force $F$ and test piece diameter $d$ was designed and materialized. The conditions of a full factorial experiment with three independent variables at three experimental levels were taken into consideration. By mathematical processing of the experimental results, power type empirical mathematical models were determined. The analysis of the empirical mathematical models showed that only the increase of the ball diameter led to a decrease of the groove depth, while in the other cases, the increase of the independent variables has a result in an increase of the dependent variable. As main limitations of the technology investigated in this paper, we can mention the application only in the case of metallic materials characterized by a certain plasticity and the need to have adequate processing equipment. In the future, there is the intention to extend the experimental research, taking into consideration other steels used in the field of machine building.

6. References
[1] Odintsov VG 1981 *Final processing of details and diamond by burnishing vibroburning* (Moscow: Mashinostroenie)
[2] Nagîţ G., Slătineanu L, Dodun O, Rîpanu MI, Mihalache AM 2019 *J. Mater. Res. Technol.* 8 4333-4346
[3] Slavov SD, Dimitrov D 2016 *Evraziiskii Soiuz Ucenyh –Technicheskii Nauki* 25 11–22
[4] Georgiev DS, Kristev KA, Slavov SD 2002 *Methodology for measurement the parameters full area and lubricant ability of surfaces manufactured by vibratory ball burnishing process* Mashinostroitelna Tehnika i Tehnologii (in Bulgarian) (Varna: Tehnicheskii Universitet)
[5] Patel MK, Patel MD 2012 *Int. J. of Res. in Engg. & Appl. Sci.* 2 372-381
[6] Garcia-Granada AA, Gomez-Gras G, Jerez-Mesa R, Travieso-Rodriguez JA, and Reyes G 2017 *Mater. Manuf. Process.* 32 1279-1289
[7] Nikonova T, Zhetessova G, Yurchenko V 2018 *Mathematical modeling of vibroburning of the hole of cylinder J. of Appl. Engg Sci.* 16 5-10
[8] Teimouri R, Amini S, Bami AB 2018 *Evaluation of optimized surface properties and residual stress in ultrasonic assisted ball burnishing of AA6061-T6 Meas.* 116 129–139
[9] Shneider YG, Guzok YV 1973 https://link.springer.com/content/pdf/10.1007%2FBF01155643. pdf Accessed: 13.04.2020
[10] Dmitriev AY, Nikonov Y, Kuznetsov VP 2011 Proceedings of XXXIX International Summer School–Conference APM Advanced Problems in Mechanics (St. Petersburg) 114-120
[11] Matalin AA, Svinitskaya VG 1977 Met. Sci. and Heat Treat. 19 1054–1057
[12] Nagîţ G, Slătineanu L, Braha V 1996 Device for vibrorolling of the external cylindrical surfaces (in Romanian). Romanian Patent 118007
[13] Creţu G 1992 The basis of experimental research. Laboratory guide (in Romanian) (Iaşi: “Gheorghe Asachi” Technical University) pp 27–35