Modelling the dependence between regular reliefs ridges height and the ball burnishing regime's parameters for 2024 aluminum alloy processed by using CNC-lathe machine

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Abstract. New approach for obtaining regular reliefs onto cylindrical and tapered surfaces, by using ball burnishing process, performed on CNC-lathe machine having C-axis installed, is presented. It allows to simplify the burnishing tool and to perform the burnishing operation on the same lathe machine as previous cutting operations. The equations for the points coordinates calculation of the needed complex ball tool trajectory are shown. For their approbation, and in order to obtain a stochastic model which established the relation between the ball burnishing regime parameters (deforming force F, and feedrate f) and resulting height (Rz) of regular reliefs cells boundary ridges, an experimental investigation is carried out, using 2024-T3 aluminum alloy, and the methodology of the rotatable experimental plans. The corresponding response surface of the model is given and discussed. Conclusions about the advantages and disadvantages of the approach are given, and also for the suitable application of the obtained stochastic model.

1. Introduction

Machine parts with cylindrical or tapered shape, which are made of non-ferrous metals like bronze or aluminum alloys sometimes are combined with rubber elements or coatings and work together in different mechanisms. As example can be highlighted silicone rubber rollers for peripheral hot stamping of cylindrical shapes and roll on decorating flat or curved surfaces, high pressure rubber roller for plastic printing machines, water lubricated rubber shaft bearings for propellers, heavy duty hydro-cylinders or rollers for rubber bands from industrial conveyors, or packaging machines, etc.

Operational conditions in which such pairs work, however, in most cases are apart from the optimal. They include high contact pressures combined with high temperatures, bad lubrication conditions, contact with abrasive substances or rough contact surfaces, etc. Often these operational conditions lead to intensive wear and fatigue failures of the inner metal parts, and of the outer rubber elements (or coatings). Intensive wear of the contact surfaces of rubber and metal parts also often happens, when they slide between each other [1-5]. As a result, the operation characteristics of such parts deteriorate fast, and this leads to loss of tightness in the contact seals, unacceptably large clearances, uneven tightness of the contact, etc. The results, obtained from the conducted experimental investigations, show that one of the most important factors, which have great influence on the operation parameters of such machine parts, is the roughness characteristics of their contact surfaces [4, 5]. If any of the well-known finishing processes, such as finish turning, grinding, or superfinishing was applied, the resulting roughness (in the
vertical section) has sharp peaks and valleys (albeit with a small height), combined with small steps between them, which do not ensure the low rate of wear. If deep rolling or classical ball burnishing (BB) was applied as a finishing process, the resulting surface will be very smooth (see Figure 1, a), but in this case the ability to hold-up enough lubricant between the sliding surfaces will be decreased significantly. Moreover, the expulsion of the dust and/or the wear's products out of the contact zone also will be more difficult, which additionally will increase the effects of wear. Therefore, in order to avoid the negative effects due to sharp peaks in the roughness profile after the commonly used cutting finishing processes, or very smooth surfaces, obtained after classical roll or ball burnishing, a little different finishing process is subject of interest in the present work.

The first goal of the work is to find a way for effective implementation of the BB process in order to form specific roughness onto cylindrical and tapered surfaces of the parts. The second one is to define a stochastic model and establish the relation between the RR’s roughness height (by using Rz-criterion) and the basic regime parameters of BB for a workpiece, made of 2024-T3 aluminum alloy. This material is chosen because it is used in applications, requiring high strength to weight ratio, as well as good fatigue resistance.

2. Advantages of the Regular Reliefs, formed by Vibratory Ball Burnishing process

There is a modification of BB, which can significantly improve the above-mentioned drawbacks of the classical finishing processes. It is called “Vibratory Ball Burning” (VBB) process [5]. The VBB possess many of the advantages of classical BB in regard to increase the surface integrity parameters. In contrast to BB, however, when VBB is applied, it is possible the so called “Regular Reliefs” (RR) to be formed onto planar, cylindrical, tapered, and even complex surfaces [5, 6, 7]. In fact, the VBB has the same basic process parameters as BB, but in this case the deforming element (which can have only a spherical shape) performs an additional oscillation movement (see Figure 1, b) with a certain amplitude and frequency, depending on the desired shape and size characteristics of the obtained RR.

![Diagram of Classical and Vibratory Ball Burnishing Processes](image)

**Figure 1.** a) Classical Ball Burning process diagram for rotational parts; b) Vibratory Ball Burning Process diagram; c) and d) Regular Reliefs from IV-th type after Vibratory Ball Burning process.

Combining all three movements (the rotation of the workpiece n, min⁻¹, the linear movement of the ball f, mm/turn, and its additional oscillating movement with an amplitude e, mm and frequency i), shown on Figure 1, b, a near to sinusoidal complex trajectory of the ball tool can be obtained. Pressing the ball with certain force F, N into the processed surface, a certain amount of plastic deformation can be achieved in the surface layer, which depends on the physical and mechanical characteristics of the workpiece material. In this way, a continuous plastically deformed trace with a certain depth and width is formed after the ball tool passage onto the burnished surface. Because the ball tool performs a complex relative movement, the plastically deformed trace produces specific patterns (i.e. RR), which can have different patterns. The possible combinations of RR are classified into five different types [5]. Of particular interest are the RR of the IV-th type, because they fully cover the burnished surface and the formed cells with a hexagonal (see Figure 1, c) or a rectangular (see Figure 1, d) shape. The inner zone surface of the RR’s cells has very small roughness heights (Rz = 0.02 – 3.2, µm), but the cells boundaries ridges (formed from self-crossing of the plastically deformed trace) have greater heights (Rz = 15 – 110, µm) [5]. The distances (or the so-called “steps”) between the RR’s cells ridges varies from 200 to 1500, µm, which, in combination with the ridges heights, defines the small slopes of the peaks profile. These
topology characteristics of RR provides increased ability to hold lubricant and products from wear into the resulting relief cells, and in this way facilitates the contact conditions, in comparison with the smooth burnished surfaces. Last, but not least, the VBB method is a waste-free technology, which makes it particularly suitable for use with non-ferrous metals, due to their higher cost, in comparison with ferrous metals.

3. Application of VBB to form RR onto rotational parts, using CNC-lathe machines

The VBB traditionally is performed, using manually controlled lathe machines, equipped with (specially designed) additional VBB-tool(s) that provide the oscillations, in order to assure the needed complex trajectory of the ball [5, 8] (see Figure 2, a). This approach, however, has some basic drawbacks, related to the manually controlled lathe machines kinematical limitations and the excitation of forced oscillations. They can be avoided, if the VBB is adapted for implementation with contemporary CNC-lathe machines (see Figure 2, b).

![Figure 2. a) VBB process performed on manually controlled lathe; b) BB process performed on CNC-lathe.](image)

The complex tool trajectory, needed for forming RR, can be mathematically generated in advance and converted into a numerical control (NC) program for CNC lathe. Using the integrated capabilities for interpolation of two or more linear and/or rotary axes in contemporary CNC machines avoid the need to use excited oscillations of the deforming tool. This, important in VBB regime component, can be skipped in the BB process implemented on CNC lathe, but without losing the capabilities to form RR of all types. As a consequence, the deforming tool design becomes much more simplified in comparison with VBB, and this allows utilization of standardized (commercial) ball tools for BB. Using standardized tools gives opportunity to perform the BB operation on the same lathe machine (after finishing of previous cutting operations), and thus there is no need to move the workpiece to another, specially equipped for VBB, machine. Furthermore, the contemporary CNC lathes offer much more stability, rigidity, positioning accuracy, and speed/feed rates than the manually controlled ones, which results in higher productivity and lower cost of production.

To calculate the ball tool trajectory points X,Y,Z-coordinates for cylindrical and tapered surfaces, the following equations are used:

\[ Z_i = L \cdot \left( \frac{i}{p} + \frac{d}{D-d} \right) + e \cdot \sin \left( \frac{2\pi i n}{p} \right) \]  

\[ X_i = Z_i \cdot \left( \frac{D-d}{L} \right) \cdot \cos \left( \frac{2\pi i n}{p} \right) \]  

\[ Y_i = Z_i \cdot \left( \frac{D-d}{L} \right) \cdot \sin \left( \frac{2\pi i n}{p} \right) \]

where: \( D, \text{ mm} \) – diameter of the cylindrical surface (greater diameter of the tapered surface); \( d, \text{ mm} \) – smaller diameter of the tapered surface; \( L, \text{ mm} \) – length of the cylindrical/tapered surface; \( 2e, \text{ mm} \) – amplitude of the ball tool oscillation; \( n, \text{ mm} \) – distance (or step along to Z-axis) between ball tool positions for one full rotation of the workpiece; \( p \) – number of trajectory points; \( i (i = 0...p - 1) \) the index of a trajectory point; \( j, \text{ osc./rev} \) – the number of ball-tool forward-backward movements, per one revolution of the workpiece.
When the processed surface is cylindrical, the condition \( d \approx D \) must be satisfied. Otherwise, the denominator \((D - d)\) of the formula for calculating the Z-coordinates will be zero. It is advisable the difference \((D - d) = 0.0001, \text{mm}\), if the movement increment of the CNC axes is 1, \(\mu\text{m}\).

Using the following formulas:

\[
R_i = (X_i^2 + Y_i^2)^{1/2} \quad \text{and} \quad \theta_i = \tan^{-1}\left(\frac{Y_i}{X_i}\right),
\]

calculated by (1) - (3) points coordinates can be transformed from Cartesian into Polar coordinates, because they are more suitable to place in the NC code, when the CNC-lathe has C-axis on the spindle installed. These points coordinates can be transferred into NC code, using a suitable CAM software and postprocessor. The NC code also can generate directly, if a mathematical software (such as Math Lab, Mathcad, SMath studio, etc.) is used to, concatenate the coordinates into appropriate G-code.

### 4. Stochastic modelling RR’s topography heights depending on the BB regime parameters

An experimental investigation is conducted to obtain a stochastic model that describes the relations between main regime parameters: deforming force \( F, \text{N} \) and federate \( - f, \text{mm/min} \), over resulting height \( R_z, \mu\text{m} \) of RR’s cells boundary ridges for 2024-T3 aluminum alloy. The 2024 aluminum alloys approximately include 4.3-4.5% copper, 0.5-0.6% manganese, 1.3-1.5% magnesium, and less than 1% other elements. T3 tempered rod has a tensile strength of 421 MPa, yield strength of 272 MPa, and elongation of 11%.

The present experimental investigation is conducted in accordance with the methodology of rotatable design of experiment [9]. For modelling the RR’s cells ridges height, the following second order stochastic model has been introduced:

\[
Y = b_0 + X_0 + b_1 \cdot X_1 + b_2 \cdot X_2 + b_{12} \cdot X_{12} + b_{11} \cdot X_1^2 + b_{22} \cdot X_2^2
\]

The matrix of two-factorial design with interaction and varying variables (deforming force \( F=500 \pm 212 \text{ N and federate, } f=300 \pm 106 \text{ mm/min} \)) is shown in section “Experimental design” in Table 1. These two regime parameters are chosen, because it has been established that they have the major impact on plasticly deformation of the surface layer at BB [6, 7]. The other parameters of BB are, as follows: the amplitude of the ball tool oscillation is \( e = 1 \text{mm} \), the number of ball-tool forward-backward movements per one revolution of the workpiece \( j = 2200, \text{osc./rev} \), the diameter of the deforming ball tool is \( \Omega 12 \text{ mm} \), and as a lubricant Mobil DTE 25 hydraulic oil is used.

**Table 1.** Matrix of coded variables, measuring and calculating results of RR’s cells ridges height, \( R_z \)

| Exp. No | \( X_0 \) | \( X_1 \) | \( X_2 \) | \( X_{12} \) | \( X_1^2 \) | \( X_2^2 \) | \( F, \text{N} \) | \( f, \text{mm/min} \) | \( \text{Experimental} \) | \( R_z, \mu\text{m} \) | \( \text{Stochastic} \) | \( R_z, \mu\text{m} \) | \( \text{Difference} \) | \( \% \) |
|---------|------------|------------|------------|-------------|------------|------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|--------|
| 1       | 1          | 1          | -1         | 1           | 1          | 1          | 288            | 194            | 6.72           | 6.47           | 3.92           |                 |                 |        |
| 2       | 1          | 1          | -1         | -1          | 1           | 1          | 712            | 194            | 9.23           | 9.56           | 3.48           |                 |                 |        |
| 3       | 1          | -1         | 1          | 1           | 1           | 1          | 288            | 406            | 17.55          | 17.51          | 0.21           |                 |                 |        |
| 4       | 1          | 1          | 1          | 1           | 1           | 1          | 712            | 406            | 26.82          | 27.37          | 3.92           |                 |                 |        |
| 5       | 1          | 1.414      | 0          | 0           | 2           | 0          | 200            | 300            | 14.78          | 15.04          | 1.74           |                 |                 |        |
| 6       | 1          | 1.414      | 0          | 0           | 2           | 0          | 800            | 300            | 24.77          | 24.19          | 2.36           |                 |                 |        |
| 7       | 1          | 0          | -1.414     | 0           | 0           | 2           | 500            | 150            | 0.63           | 0.64           | 1.04           |                 |                 |        |
| 8       | 1          | 0          | 1.414      | 0           | 0           | 2           | 500            | 450            | 21.34          | 21.04          | 0.15           |                 |                 |        |
| 9       | 1          | 0          | 0          | 0           | 0           | 0           | 500            | 300            | 16.82          | 16.72          | 0.58           |                 |                 |        |
| 10      | 1          | 0          | 0          | 0           | 0           | 0           | 500            | 300            | 16.63          | 16.72          | 0.62           |                 |                 |        |
| 11      | 1          | 0          | 0          | 0           | 0           | 0           | 500            | 300            | 16.91          | 16.72          | 1.17           |                 |                 |        |
| 12      | 1          | 0          | 0          | 0           | 0           | 0           | 500            | 300            | 16.52          | 16.72          | 1.22           |                 |                 |        |
| 13      | 1          | 0          | 0          | 0           | 0           | 0           | 500            | 300            | 16.70          | 16.72          | 0.02           |                 |                 |        |

The experimental plan is characterized with a minimal number of experimental data. It contains a basic part \( 2^k \) (where \( k \) is number of varying variables in the process), a symmetric set of eight points (1 – 8) around the center of the design, and five points of repetition (9 – 13) in the center of design (see Figure 3, a). A cylindrical rod with \( \Omega 40 \times 350 \text{ mm} \), made of 2024-T3, is used as a workpiece. The outer diameter of the rod is previously machined by finishing, turning to \( \Omega 38 \text{ mm} \) and initial roughness \( R_z = \)}
increased the initial roughness deformation in the surface layer \( R_z \) and \( f = 450 \text{ mm/min} \). When the deforming force and maximum \( R_z = 31.9 \mu m \) is observed obtained on the considered adequate.

The results obtained from stochastic analysis and experimental ones carried out show that the minimum \( R_z \) value \((1.24 \mu m)\) is obtained, when the deforming force has value of \( F \approx 500 \text{ N} \) and feedrate \( f \approx 150 \text{ mm/min} \), and the maximum \( R_z = 31.9 \mu m \) is observed, when both regime parameters have maximum values \((F= 800, \text{ N} \) and \( f= 450 \text{ mm/min} \)). When the deforming force and the feedrate have minimum values, however, the \( R_z \)-criterion increases its values up to \( R_z = 2.53 \mu m \). This can be explained with the small rate of plastic deformation in the surface layer, when the deforming force and feedrate have low values. In this case, the initial roughness can have an impact on the measured values for \( R_z \). If the deforming force is increased, the roughness height is decreased to a certain point, and with a further increase of the \( F \), the

The dispersion homogeneity of the cells ridges height results is examined, using Cochran’s criterion for level of reliability \( P=0.95 \). The model’s coefficients \( b_0, b_1, b_2, b_{12}, b_{11}, \) and \( b_{22} \) are calculated and checked for significance, on the basis of the measured experimental results (see Table 1). As a result, their coded values are obtained, as follows: \( b_0 = 16.723, b_1 = 3.238, b_2 = 7.213, b_{12} = 1.690, b_{11} = 1.449, b_{22} = -2.945. \)

The stochastic model (5) with its coded coefficients passed successfully the check for significance, using Student’s F-criterion, and after decoding, its physical form is obtained:

\[
R_z(F,f) = 0.000032 \cdot F^2 - 0.000262 \cdot f^2 + 0.000075 \cdot F \cdot f - 0.039 \cdot F + 0.188 \cdot f - 15.576 \tag{6}
\]

![Figure 3. a) Diagram of rotatable plan for two variables X(F) and X(f); b) The response surface which corresponding to the stochastic model (6).](image)

A comparison of the experimental and the stochastic results is shown in Table 1, and a graphical representation of the response surface, which corresponds to the (6) is presented in Figure 3, b.

5. Results and discussion

The results obtained from stochastic analysis and the multi-factorial experimental rotatable design carried out show that the results of \( R_z \)-criterion, established in stochastic model (6) are very close to the experimental ones. The maximum percentage differences (see Table 1) are observed only at \( 1^{st}, 2^{nd} \) and \( 4^{th} \) points of the experiment, but they are not exceeding 4\%, thus the derived stochastic model can be considered adequate.

The response surface, created on the basis of the stochastic model (6), is a segment of a hyperbolic paraboloid and is presented in Figure 3, b. It reveals the way of influence of the two regime parameters on the \( R_z \)-roughness criterion of RR. Analyzing it, it is seen that the minimum \( R_z \) value \((1.24 \mu m)\) is obtained, when the deforming force has value of \( F \approx 500 \text{ N} \) and feedrate \( f \approx 150 \text{ mm/min} \), and the maximum \( R_z = 31.9 \mu m \) is observed, when both regime parameters have maximum values \((F= 800, \text{ N} \) and \( f= 450 \text{ mm/min} \)). When the deforming force and the feedrate have minimum values, however, the \( R_z \)-criterion increases its values up to \( R_z = 2.53 \mu m \). This can be explained with the small rate of plastic deformation in the surface layer, when the deforming force and feedrate have low values. In this case, the initial roughness can have an impact on the measured values for \( R_z \). If the deforming force is increased, the roughness height is decreased to a certain point, and with a further increase of the \( F \), the
Rz starts to increase its values again. This can be explained with the comparatively greater amount of metal that pushes the deforming element in front of it, as it follows its complex trajectory. The increasing of the feedrate intensifies the degree of plastic deformation in the surface layer of the workpiece, and contributes further to increasing the height of the ridges of the RR’s cells.

6. Conclusions

Based on the analysis of the BB’s process requirements for creating RR and the functional capabilities of the contemporary CNC-lathe machines, the following conclusions could be made:

- Ball burnishing, as a finishing process was successfully implemented in order to form regular reliefs of the IVth type onto cylindrical outer surfaces, using CNC-lathe machine, which has C-axis;
- On the basis of equations (1) – (4), it is possible to calculate the needed ball tool trajectory points coordinates for both cylindrical and tapered surfaces. They can transform easily into a corresponding NC-code for CNC-machine, using any CAM or a suitable software for engineering calculations;
- The main advantages of the implementation of the BB on CNC-lathe machines are: simplifying the design of the tools for BB (even standardized commercial tools could be used); the BB operation can be performed on the same machine as other lathe operations, i.e. there is no need to move the workpiece from one to another equipment.
- As a disadvantage of the present approach can be listed the need of additional C-axis (which allow interpolation) installed of the CNC-lathe machine, and also in some cases the appropriate software for generating the NC-code, which can be costly;

On the basis of the conducted experimental investigation, the stochastic model (6) is derived. It describes the influence of the regime parameters of BB deforming force F, and feedrate f. The model can be used for prediction what will be the RR’s cells ridge heights (expressed with Rz roughness criterion), when certain values of the regime parameters are set. It is also suitable, if the RR must have cells ridges with a certain height, what BB’s regime parameters values have to be chosen, in order the needed Rz-criterion value to be achieved.

The authors consider the present work as first steps in the study of the presented issues. Our future work will focus on the study of the influence of the other regime parameters of the BB process on some other topographic characteristics of the RR, as well as on other materials.

7. References

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