

# A study on the variability of the pressing force during processing of regular shaped roughness by using new kinematical scheme for ball-burnishing process

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**Abstract.** In many studies of the ball-burnishing processing often assumes that the pressing force applied to a ball tool remains a constant during the whole processing. The present study focused on measuring the compression force continuously during conducting ball-burnishing process, using new kinematical scheme. The combinations of values of the regime parameters are according to four factors full factorial experiment design with two levels per factor of type  $2^4$  and 4 replications per run. The experimental results are processed statistically and using techniques such as Pareto and ANOVA, the regime parameters of the process are sorted by degree of significance.

## 1 Introduction

In the cold forming processes like burnishing, vibratory ball burnishing, thread or spline rolling, there takes place the deformation of the surface layer, which modifies its physical and mechanical characteristics. The strain-hardening phenomenon introduces some compressive stresses into the surface layer, which results with the increase of surface hardness and endurance strength [2,3,5]. The process of burnishing also uses as finishing machining operation after which, the workpiece has improvements such as better surface roughness, decrease of the formation of fractures, fatigue strength, and increase of the wear resistance [3,5]. These positive improvements are dependent on the regime parameters of the (vibratory) burnishing process such as feed rate, burnishing (compressive) force, ball diameter, etc. The influence of these parameters, used while conducting the ball burnishing process for improving surface roughness, micro hardness, fatigue strength, etc., have been examined in numerous experimental studies over the years. As a result, there are obtained many functional dependencies between the regime parameters and the roughness, strength and physical and mechanical characteristics of workpieces (made of different types of steels, non-ferrous metals, etc.), processed by different types of cold forming processes. Significant part of conducted experiments are focused on determination of the impact of the pressing force applied to the ball tool, which is one of the most significant regime parameters of these processes [5]. When describing the experimental studies, however, many authors consider

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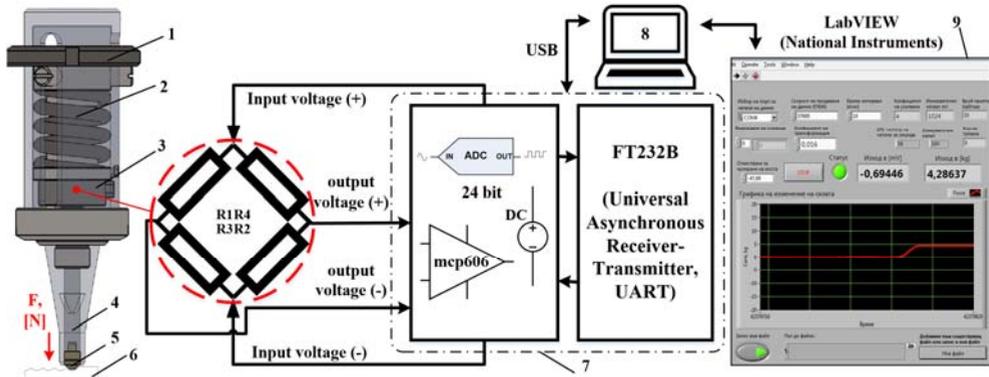
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that once the required nominal value of the pressing force has been set, it remains constant during the whole processing. That assumption may be not always correct even when processing flat surfaces from the prismatic workpieces for example. This is because the burnishing process actually performs on real workpiece, by using real instruments and real machines, which usually have certain surface irregularities, deviations in its dimensional tolerances, and deformations caused by external loads. Therefore, it is interesting to study what is actually the variability of the pressing force during ball burnishing process, as this may have an impact on the degree of uniformity of resulting plastic deformation in surface layer, and can reduce the effect of the improvements in the surface layer of the burnished workpieces. In this regard, the main objective of the present work is to measure experimentally what is the variability of the pressing force when processing flat surfaces from a steel plate by ball burnishing process (using a new kinematical scheme), and how the main regime parameters influenced on that variability.

## 2 Methodology of experimental investigation

### 2.1 Setup for experimental measuring the pressing force during ball burnishing process

Fig. 1 shows a measurement setup, used for determining the nominal value and deviations of the pressing force, during ball vibratory burnishing processing of flat surfaces. It consists of specially designed deforming ball tool [4] which integrated miniature force sensor, type FCM ( $F_{nom}=5$  kN), SIKA, Dr. Siebert&Kühn GmbH & Co (pos. 3). A standard manufactured helical compression spring with ground ends provides the needed pressing force of the tool. The spring, which is used, gives maximum force up to 3200 N at maximum deflection length of 48 mm. The helical spring (pos. 2) presses the force sensor (pos. 3).



**Fig. 1.** Setup for measurement the pressing force during ball burnishing process.

The front part of the force sensor (pos. 3) presses the head of the plunger (pos. 4). The plunger transfers the force from the spring to the ball burnishing element (pos. 5), which rolls along a complex trajectory on processed surface of the workpiece (pos. 6). The complex trajectory provides by using appropriate CNC milling machine [3,5]. This is necessary for obtaining the desired surface roughness with a regular micro shape. Position 7 of Fig. 1, shows a principal block diagram of a device for amplification and conversion the signal from the force sensor to a PC. The device provides a stabilized DC input of 10 V, 50 mA, and thereby the measuring range of the output signal of the sensor is varied from 0 to 20 mV when changing the pressing force in the range between 0 and 5 kN. The output signal from

the sensor is amplified by precise low-noise amplifier type MCP606 (Microchip) with adjustable amplification factor to an appropriate level for converting from analogue to digital form, using the built-in ADC. The converted signal is transmitted to the universal asynchronous receiver-transmitter (type FT232B on FTDI) for conversion into serial data for transmission to a PC (pos. 8), through the USB 2.0 interface. For adjusting the operating mode of the microcontroller, as well as to visualize and record the measurement data of the force, a specialized software product (pos. 9) based on the integrated program environment LabVIEW (NI) is developed. Thus, it is possible to balance the force sensor, to adjust the factor of amplification, to change the rate of sampling, etc. Moreover, it is possible to show the measured instantaneous values of the pressing force digitally and in graphic form. The software allows recording the measured data from the force sensor in CSV (comma-separated values) file format, supported by MS Excel for further statistical analysis of the data.

## 2.2 Design of the experimental research

Four factors full factorial experiment design with two levels per factor of type  $2^4$  and four replications per run [1] is carried out to determine the degree of influence of the main regime factors of the process. The design of the experiment is shown in “Experimental design” section of the Table 1.

**Table 1.** Full factorial design plan and results for coefficient of variation of the pressing force F.

Run	Experimental design				Experimental results (coefficient of variation)			
	F, N	i	e, mm	s, mm/min	CV 1	CV 2	CV 3	CV 4
1	1059.1	600.15	1	300	0.737	0.514	0.778	0.556
2	1059.1	600.15	2.5	150	0.606	0.654	0.599	0.510
3	1059.1	1200.15	1	150	0.522	0.608	0.587	0.407
4	1059.1	1200.15	2.5	300	0.531	0.721	0.569	0.421
5	1735.8	600.15	1	150	1.531	1.702	1.443	1.298
6	1735.8	600.15	2.5	300	1.605	1.564	1.285	1.213
7	1735.8	1200.15	1	300	1.406	1.543	1.286	1.185
8	1735.8	1200.15	2.5	150	1.716	1.619	1.430	1.410
9	1059.1	600.15	1	150	1.461	1.433	0.539	0.412
10	1059.1	600.15	2.5	300	1.401	1.530	0.510	0.453
11	1059.1	1200.15	1	300	1.201	1.394	0.552	0.434
12	1059.1	1200.15	2.5	150	1.641	1.716	0.571	0.477
13	1735.8	600.15	1	300	1.306	1.466	1.234	1.155
14	1735.8	600.15	2.5	150	1.516	1.508	1.216	1.188
15	1735.8	1200.15	1	150	1.258	1.463	1.254	1.129
16	1735.8	1200.15	2.5	300	1.424	1.551	1.334	1.325

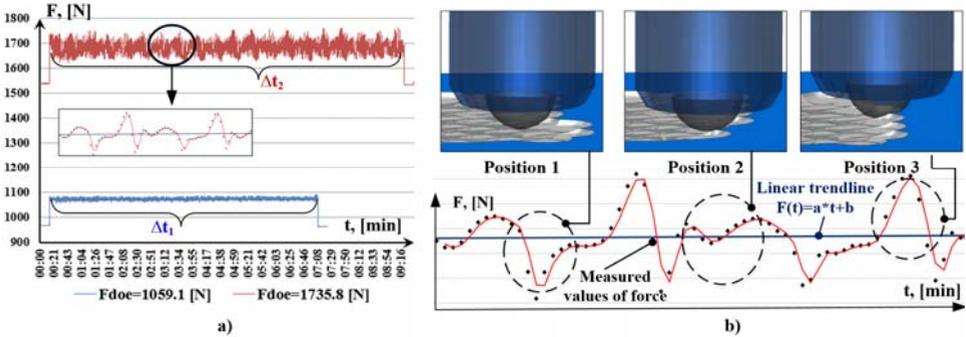
The diameter of the used ball tool (a steel ball from rolling bearing) remains the same (8 mm) in all of the 16 runs and four replications of the experimental study. Due to conducted preliminary studies of the ball burnishing process, carried out using CNC milling machines [3], the significant (adjustable) regime parameters, which mainly affect the characteristics of the processed surface, have been established. They are as follows:

- F, N– applied external force (by helical spring) on the ball tool;
- i – the set number of the sinusoids along the path travelled by instrument, which determines the height of the obtained cells from roughness with regular microshape;
- e, mm – the set half of the amplitude of the sine wave, related to the width of the obtained cells from roughness with regular microshape;
- s, mm/min – the set feed rate of the ball tool following the sinusoidal trajectory, provided by the CNC milling machine;

The experimental specimen is made of sheet stainless steel, grade 316L ASTM (Cr17 Ni11Mo2) with a thickness  $\delta=4$  mm, which has physical and mechanical properties, as follows:  $\rho=8000$  kg/m<sup>3</sup>;  $E=193$  GPa,  $R_{p0.2}=353$  MPa,  $R_{p1.0}=394$  MPa,  $R_m=628$  MPa,  $A_5=49\%$ ,  $A_{50}=47.2\%$  and  $HRB=82$ . The plate has a square shape and dimensions 400x400 mm. The sections, corresponding to the rows of the experimental design from Table 1 which processed by ball burnishing, have rectangular shape and dimensions 40X10 mm.

**2.3 Statistical processing of measured data**

Measured data for the pressing force, obtained during processing by vibratory ball-burnishing for all runs and replications according to the experimental design plan, shown in Table 1, are imported into MS Excel, where displayed through XY line (or scatter) charts. Fig. 2.a shows graphics of two measurements, captured under the nominal values of the pressing force  $F$ , respectively 1059.1, and 1735.8 N. As seen in Fig. 2.a, the duration of measurements is different for different rows of the experimental design ( $\Delta t_1 \neq \Delta t_2$ ). This is because the processing time depends on the regime parameters  $e$  and  $i$  and feed rate of the ball tool  $s$ . According to the experimental plan from Table 1, the shortest duration will be obtained at row №13:  $\Delta t_{min}=6:52$  min. Thus, at rate 16 SPS will be accumulated 6,500 measured values. Respectively, the longest time will be obtained at row №12:  $\Delta t_{max}=26:28$  min and 25,414 values will be accumulated. The Excel XY charts are used to identify and clipping those measured data, when the ball tool is not processing the workpiece, i.e. when it reposition from an already processed area of the specimen to the next.



**Fig. 2.** a) Examples of the XY line graphs of the measured data in Ms Excel; b) Manner of changing the pressing force depending on the current position of the ball tool.

For more accurately assess of the force variability, a least squares linear regression is used for calculate the slope and the intercept to determine whether the measured data for the pressing force have significant slope trend. Where it is found significant slope, the magnitudes of the deviations of pressing force is assessed against the least squares fitted regression line  $F(t) = a \cdot t + b$  (see Fig. 2.b). Thus, the effect of the irregularities in the geometric shape and dimensions of the specimen and the working bodies of the used milling machine is reduced. After that, the Descriptive Statistics analysis tool add-in of MS Excel is used for every run and replication of the experimental design. Because for different rows of the experimental plan the samples have different sizes and different mean values, the variability of the force is assessed by using the coefficient of variation (CV) [1]. The CV is the ratio of the standard deviation ( $\sigma$ ) to the mean ( $\bar{X}$ ), calculated using the following formula:

$$CV = (\sigma / \bar{X}) \cdot 100 \tag{1}$$

Calculated CVs using (1) are given in the section “Experimental results” of the Table 1. To build the effects plot (see Fig. 3.a), the average effects  $Avg_{low}$  and  $Avg_{high}$  are determined for the four regime parameters, using the following formulas:

$$Avg_{low} = \frac{1}{8} \cdot (\sum_{i=1}^8 CV_i^{low}) \tag{2}$$

$$Avg_{high} = \frac{1}{8} \cdot (\sum_{i=9}^{16} CV_i^{high}), \tag{3}$$

Where:  $CV_i^{low}$  – are those eight results from Table 1, where the regime parameters have low level values;  $CV_i^{high}$  – the other eight results, where the parameters have high level values.

Based on (2) and (3) the effect of each of the four regime parameters on the variability of the pressing force can be calculated using the formula:

$$Eff_{(F),(i),(e),(s)} = Avg_{high} - Avg_{low} \tag{4}$$

To visualize the effects of a design experiment, Pareto analysis technique is used for sorting the regime parameters according to their levels of significance (see Fig. 3.b) based on calculated by using (4) values of effects. Additionally an analysis of variance [1] (see Fig. 3.c) is carried out to calculate the Fisher-values of the factors. For confidence level 95% and total degrees of freedom  $DF = (Runs \cdot Repplications) - 1 = (16 \cdot 4) - 1 = 63$ , the critical Fisher value is 3.993.

### 3 Results and discussion

Comparing the ranges of variation, when the pressing force has low nominal value  $F=1059.1$  N, the variability is amended from  $\Delta F_{min}=25.3$  N to  $\Delta F_{max}=105.8$  N. At the high level of the force  $F=1735.8$  N, this amendment is from  $\Delta F_{min}=84.2$  N to  $\Delta F=171.5$  N. Thus, the range of variability is amended from 5 to 10% of the nominally assigned compression forces. The main cause of variability of the pressing force is represented in Fig. 2.b. It is seen how the pressing force varies within one full reciprocation of the ball-tool following the toolpath during the process of ball burnishing of flat surface of the specimen. In Position 1, the ball-tool is located over already burnished region of the specimen. In this position, the pressing force has a minimum value because the ball falls within the valleys of regular roughness, and the spring expands slightly in comparison to its preliminary tensioning. In Position 2, the pressing force has an average value and slightly fluctuates because the ball passes over the heights, which surrounding the cells of the regular roughness. In Position 3, the spring is shrinking additionally in comparison to its preliminary tensioning.

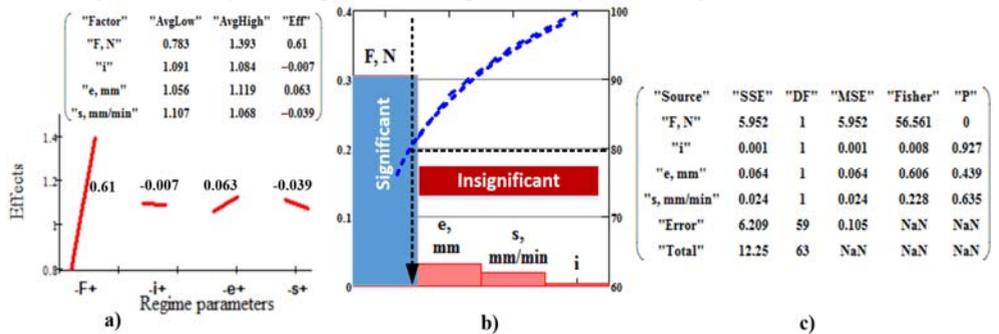


Fig. 3. a) Effects plot of the regime parameters; b) Pareto histogram and cumulative graphs, based on the effects; c) ANOVA table with calculated statistics and Fisher-values of the process factors.

This is because the ball goes up over not yet deformed region of processed surface. In addition, this is the main reason for observed short-term pulsations in the values of the pressing force.

Obtained data after evaluation of the effects and carried out Pareto analysis (see Fig. 3.a and 3.b) shows that the variation mainly depends on the magnitude of the nominal value of the pressing force  $F$ . With increasing the magnitude of the pressing force, proportionally increases observed variability and vice versa. The other three regime parameters ( $i$ ,  $e$ , and  $s$ ) have a much smaller impact on the variability of the pressing force. After conducted ANOVA analysis (see Fig. 3.c), the factor  $F$  was assessed as a significant at the 95% level of confidence since his Fisher-value =56.561 is greater than critical Fisher value=3.993. The  $F$ -values of the other regime parameters are less than the critical Fisher value. Thus, conducted analysis of variance reinforces the subjective conclusion derived from the Pareto histogram plot.

## 4 Conclusions

Based on conducted experimental study and the undertaken analysis of the obtained results could be made following conclusions:

- The established experimental setup (see Fig. 1) including miniature force sensor, device for amplification and signal conversion, and specially created software, allows precise measuring the pressing force (in real time) as well as visualization and recording the measurement data in appropriate file format. This significantly facilitates the subsequent processing of the measurement data in suitable software such as Excel, Mathcad etc.
- The observed variation of the pressing force  $F$ , during ball-burnishing process carried out by new kinematical scheme (using CNC milling machine) on flat surfaces mainly depends on the pre-set magnitude of this regime parameter. The remaining three regimes parameters ( $i$ ,  $e$ , and  $s$ ) have a negligible impact on the variability of the pressing force. This gives grounds they do not take into consideration for future research.
- The measured variability reaches a maximum of 10% ( $\pm 5\%$ ), compared to the nominal pre-set level of the pressing force. Largely, this irregularity is due to cyclical crossing of the ball-tool between the already deformed and have not yet processed surface of the workpiece (see Fig. 2.b), resulting in a periodic shortening and extending of the helical spring, which provides the pressing force.

Further research of the collective will be focused on examining the degree of variability of the pressing force when processing workpieces with a more complex shape of its functional surfaces, using ball-burnishing process.

## References

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