TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 67, Issue Special IV, August, 2024

EXPERIMENTAL RESEARCH OF THE ACTUAL SPEED REACHED WHEN PROCESSING REGULAR RELIEFS USING AN ADVANCED DEFORMING TOOL FOR BALL BURNISHING

Stoyan SLAVOV, Georgi VALCHEV, Oleksandr MARKOV

Abstract: *The current work describes the design and operational principle of an advanced tooling system that works with Computer-Numerical-Control (CNC) milling machines, which is used for creating specific regularly distributed surface patterns onto planar surfaces, based on ball-burnishing (BB) approach. The proposed tooling system in the current work has capabilities for measuring the deforming force and accelerations along X, Y and Z-axes during the BB-operation. The measured values from the tools sensors can be transmitted wirelessly to the data acquisition system, where they are combined with the measured accelerations along the X and Y-axes of the machine, so that all data is stored in a SD-memory card for further analyses. An experimental research is conducted to determine the actual speeds reached by the CNC machine using the proposed advanced tooling system. The obtained results are shown and discussed at the end of the work.*
Key words: *ball burnishing; regular reliefs; MEMS accelerometers; wireless transfer of data, actual speed and feedrate measurements.*

1. INTRODUCTION

A wide range of functional properties, including physical, chemical, electrical, mechanical, wear-resistance and/or corrosion-resistance of the machine component's contact surfaces can be enhanced using some of so-called "surface engineering" (SE) approaches. Some of the most popular techniques for SE are processes, such as [1]: vapor phase deposition, diffusion, thermal spray and welding using heat sources, such as, laser, plasma, solar beam, microwave; friction, pulsed combustion, ion, electron pulsed arc, spark, friction, induction, etc. They all use heat or electromagnetic energy to make changes in the surface layer properties. Often, the energy used to obtain certain operational properties of the machine parts surfaces is significant, which makes them highly energy-consuming and therefore not environmentally friendly. In this regard, there is a group of cold working methods, which are based on the plastic deformation of the surface layer by applying a certain load over sliding or rolling deforming elements, which perform movements following simple or complex toolpaths. There are different classifications of these superfinish operations [2], which depend on: the shape of the deforming element; number of the deforming elements that work simultaneously; type of the contact (sliding or rolling) between them and processed surface; type of materials of which they are made; the methods of application of the deforming force; the shape of the processed workpiece surface; etc.

Moreover, after the application of one of the methods, called "vibrational ball burnishing' (VBB) [3], where the deforming tool (which has a spherical shape) follows a complex toolpath, the so called "regular reliefs" (RR) can be obtained onto processed surfaces. RRs can be partially- or full-regular, depend on the density of plastically deformed traces that remains onto the surface after the ball tool passage.

Some researchers [4, 5, 6] confirm positive effects of applying ball burnishing operations over surface's physical, mechanical and topographical characteristics of the parts. For example, their application could increase wear resistance, fatigue life, corrosion resistance, etc. In addition, when RRs are formed onto surfaces, which are elements of sliding pairs, they help the friction force in the pair to be considerably reduced. This is due to the specific topography of RRs obtained by VBB and the increased abilities to retain more lubricant media into the plastically deformed traces (or into the cells in case of fully regular reliefs), in comparison with the rest of traditional finishing processes such as turning, milling, grinding, honing, and lapping. This results in obtaining a lower coefficient of friction and therefore lower energy (or fuel) consumption, especially when the friction pairs are elements of some heavy loaded manufacturing equipment or vehicles that operates in harsh working conditions, such as maritime, chemical and mining industries, as an example.

The VBB's process, however, originates from early 1970s as a modification of the classical BB-process [3] in which there is no enforced vibrations of the ball tool. Although that process was studied intensively in the 1970s and 1980s and most of the positive effects of its application were established already then, it is still not widely applied as finishing operation in manufacturing practice. In the past few decades, the main reason the VBB process to remain neglected from manufacturers was the complex trajectory of the ball tool that is needed for RRs formation. To perform needed toolpath of the deforming tool, which has near to sinusoidal shape, using "Industry 2.0" - types of machine tools, a specially designed tooling equipment for VBB has to be used.

Usually, a VBB's tooling device consists (at least) of one additional electromotor, a gear (or belt) transmission, and crank mechanism to assure the reciprocating movement of the ball tool in addition to the kinematics of the assigned milling or lathe machine. This makes its dimensions much larger than the rest of the cutting tools used in machining of the parts, which requires the VBB operation to be performed on a specially equipped machine, and separately from the rest of the machining process operations. Nowadays, such a "comfort" to use one machine for just one single operation is highly unreasonable, which explains the poor success of VBB-process as a finishing operation.

A contemporary approach for applying VBB operations using the capabilities of Computer-Numerical-Control (CNC) machine tools (or “Industry 3.0” type of equipment) has been developed in order to avoid abovementioned issues [7]. It is based on the mathematical description of the deforming element toolpath using suitable functions, according to the shape of the processed surface and the transformation into corresponding numerical code (NC), readable by the CNC system of the machine. The complex toolpath of the deforming element is executed by the linear interpolation of the CNC-machine axes. Therefore, there is no need for sophisticated tooling equipment for performing the VBB operation. The enforced vibrations of the ball tool become redundant now. Hence, the ball-burnishing tool adopt simpler design and dimensions that are comparable to other cutting tools sizes. As a result, the VBB operation can be executed immediately after the previous operations are finished on the same CNC-machine.

Simplifying the deforming tool design leads to minimizing its overall dimensions and this allows one or more miniature sensors for measuring/ monitoring of some parameters of the BB process to be installed into it. If they are connected with suitable microcontroller device, the measurements from the sensors can be gathered, processed and/or transmitted to an external computer device or stored in external memory card for further analyses.

In this way, the burnishing tool will turn into a mechatronic device, which does not simply deform the surface layer and form RRs onto it, but also is capable of measuring and reporting the condition of the BBs process parameters during the operation.

Hence, the main objective of the present work is to create an advanced tooling system for enhancing the integrity of planar surfaces by forming RRs onto them, which can operate with vertical CNC-milling machines, and collect measured data for main regime parameters of the BB process.

Review of the existing commercial solutions for burnishing tools show that they most often employ cylindrical or tapered rollers with different contours or diamond inserts, which have half-spherical tip with certain radii as deforming elements [2]. Commercial solutions with a spherical rolling deforming element, however, are hardly found on the market. Most of the burnishing tools that use spherical rolling elements are reported mainly concerning conducted experimental research on the burnishing process. Some of the published tool designs are equipped with sensor for deforming force measurement or its variability during the burnishing process.

However, except the deforming force, which is the BBs main regime parameter with the greatest impact over the surface layer characteristics, feedrate also has influence on the strain-rate of the material's surface and determines the productivity of the operation [8]. Feedrate is usually preset to certain value(s) and it is assumed that it remains constant throughout the whole BB operation. This can be the case when the deforming tool moves only along a comparatively straight-line trajectory except for the start and end sections where it accelerates and decelerates.

However, when the BB process is performed on a CNC milling machines to form RR, the ball tool must change its direction of movement constantly when following the complex toolpath needed [9]. As a result, the actual feedrate reached will be constrained by dynamical characteristics of the machine tools interpolated axes and their cycles of "acceleration – deceleration" in the different segments of the toolpath. Therefore, the feedrate of the burnishing tool, set in the numerical code for CNC control, will not actually be reached by the machine in some cases. Moreover, feedrate will not be constant in the whole length of the complex toolpath. The variability of that regime parameter will cause corresponding material strain-rate variability and may affect physical and mechanical characteristics of the processed workpiece surface layer, having an impact on its tribological behavior.

In order to research the real accelerations achieved and to investigate the actual speed limits of the burnishing tool and CNC-milling machine table movement, they should be equipped with suitable sensor(s) to acquire their actual values in different process settings and different toolpaths performed. Therefore, the main goal of the current work is to create and develop a suitable tooling system that can be used for experimental research of these aspects of the BB-process.

2. METHODS AND MATERIAL

2.1 Sensors and their disposition according to the CNC-machine axes

BB finish operations most often are applied for rotational or planar surfaces, which means the deforming tool is usually setup and fixed in the lathe's turret or in the milling machines spindle. As it is known, the lathe machines can interpolate up to two linear axes X and Z, which means that the actual feedrate movement can be performed strictly parallel to one of them, or distributed by the interpolation between them when part contour segments are chamfered or rounded. Therefore, two accelerometers have to be installed on the tool housing, which are directed perpendicularly to each of the linear axes.

If a vertical milling machine is used for BB of planar surfaces, there are three linear axes - X, Y and Z that can operate in positional mode (i.e. 2.5D interpolation) or simultaneously (i.e. 3D interpolation). In that machine configuration the burnished workpiece is fastened onto the machine table and can move along to the X- and/or Y-axes. The deforming tool is put into the vertical spindle and moves parallel to the Z-axis direction. Therefore, at least three accelerometers have to be used in that case, where each of them should be directed to each of the three linear axes of the milling machine.

To be able to measure and adjust the deforming force magnitude during the BB process, a load cell also should be implemented into the ball burnishing tool construction. The sensitive direction of the load cell should coincide with the axis at which the load is appled onto the spherical deforming element in order to measure momentary values of the deforming force.

It is highly advisable that the load cell and axes accelerometers are able to transmit measured data wirelessly to the data acquisition device, because if a wire connection is used inside the working chamber of the machine there

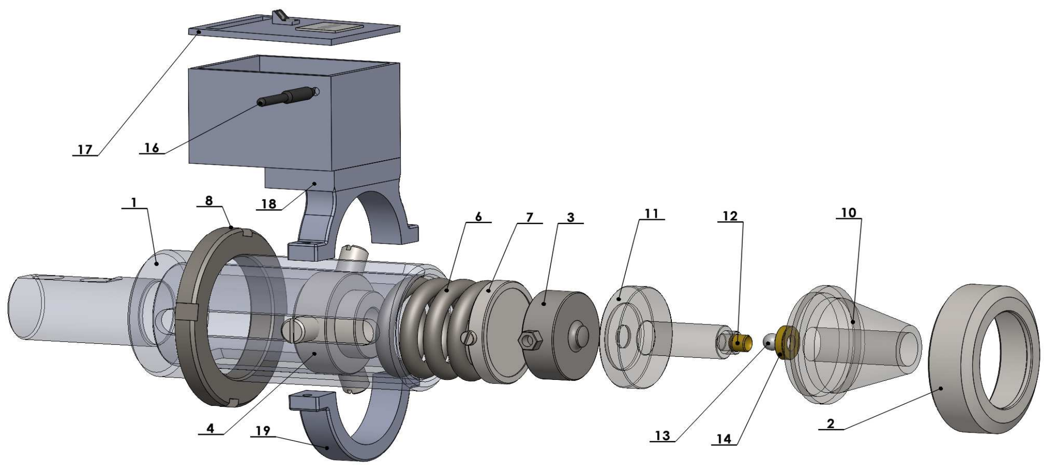


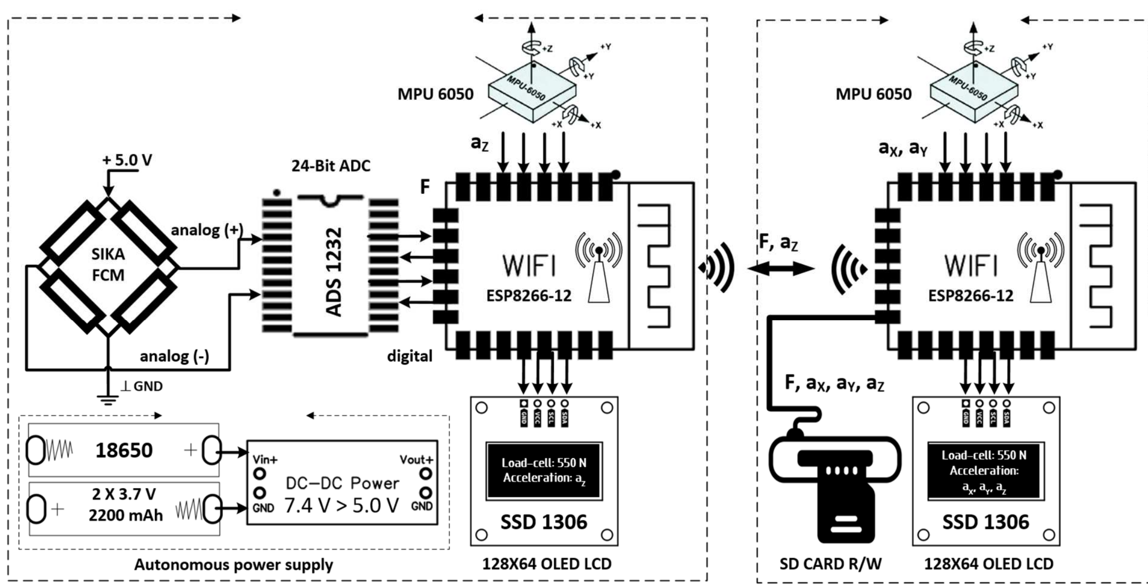
Fig. 1. Disassembled view of the burnishing tool for CNC-milling machines.

is a risk that the wires can brake due to the table, turret or spindle movements.

2.2 Design description of the burnishing tool's mechanical part.

The disassembled view of the deforming tool, which is intended to work with milling machines, is shown in Fig. 1. It is based on the previous tool design proposed in [10], [11], but in the current case the front end is altered with short tapered bushing (pos. 10) to increase its stability when burnishing planar surfaces. The load of the spherical deforming element (pos. 13) is set mechanically by the compression spring (pos. 6), which can provide up to 3200 N of deforming force in the axial direction. The spring compression level is provided by the axial position of the rear nut (pos. 8). The front-end bushings (pos. 12 and 14) are changeable in order for burnishing balls with different diameters to be used. The shank of the tool (pos. 1) has suitable shape and dimensions to mount into side lock milling tool holders of type SK40, ISO 7388-1.

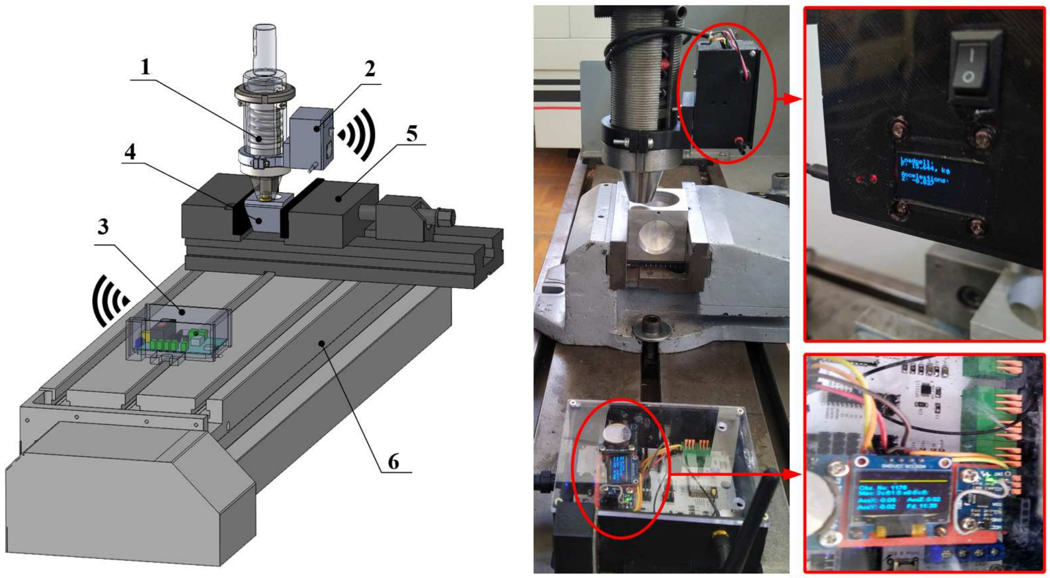
The load cell (pos. 3) used to measure the deforming force is type FCM (SIKA, DE), based on Wheatstone's resistance measuring bridge, which is capable of measuring loads of up to 5000 N. It is placed between the spring forehead (pos. 7)



a) Deforming force and Z-axis acceleration measuring, and data transmitting part

b) Accelerations in X- and Y-axes directions measuring, and data logging part

Fig. 2. A diagram of the burnishing tool's electronic components.



a) b)

Fig. 3. A typical burnishing tool setup on the CNC-milling machines: a) A diagram of the burnishing setup parts location; b) View of the burnishing tool on the milling machine.

and the plunger (pos. 11), such that the load can act on it. The electronic part of the tool is mounted into the specially designed 3D printed box (pos. 17), which is fastened by the brackets (pos. 18) around the outer diameter of the tool's housing.

2.3 Description of the tool's electronic parts

Electronic parts of the burnishing tool consists of two separate devices (see Fig. 2, 3), which have wireless connection with each other. Both of them are based on ESP8266-12 (Espressif) type system-on-chip (SoC) microcontroller unit (MCU) devices, which have ability to transfer data to each other by using Wi-Fi protocols 802.11 b/g/n (2.4 GHz), with speed up to 72.2 Mbps. One of them is attached to the burnishing tool housing (see Fig. 3, pos. 2) and the other is fastened on the milling machine's table (see Fig. 3, pos. 3). The principle circuit diagram of the deforming force and Z-axis acceleration measurement, and data transmition part is shown in Fig. 2, a). As it can be seen, it mainly consist of one ESP8266-12 MCU, one 24-Bit delta-sigma analog-to-digital-converter (ADC), model ADS1232 (Texas Instruments, US), and one six-axis gyro & accelerometer MEMS (micro-electromechanical system) device of type MPU-6050 (TDK InvenSense). The MEMS device has user-programmable three axes accelerometer, which supports programmable full-scale of accelerations in range ±2g, ±4g, ±8g, and ±16g. It also supports 400 kHz fast mode I²C type interface with the MCU. The used delta-sigma type of ADC has maximum of 23.5-bits effective resolution, and data rates up to 80 SPS (samples- per-second). That part is equipped with autonomous power supply based on two rechargeable batteries of 18650 type.

The second part of the burnishing tooling system (see Fig. 3, a, pos. 3), i.e. the "receiving and data logging part" is based on the same MCU type and MEMS accelerometer as the transmitting part. Its principle electronic circuit is shown on Fig. 2, b. As can be seen from the Fig. 2, b, here an accelerometer only is attached to the MCU to detect the accelerations along the X- and Y-axes of the CNC machine table movements. In addition, a micro-SD card reader/ writer device also is used in order to record the measurements in a suitable memory card.

Both of the parts are equipped with SSD 1306 type OLEAD LCD mini displays, which are used to visualize the measured data and to monitor the operational condition of the BB-process and the deforming tool system.

3. A TOOLING SYSTEM OPERATION ALGORITHMS

3.1. Initial calibration procedures

The operation algorithms for the tooling system transmitting and receiving parts are shown in Fig. 4, a, b. After the initialization of the used ADC and MEMS module in the transmitting part of the tool, two procedures for initial calibration of the sensors are conducted (see Fig. 4, a) [11]. The second procedure (see Fig. 4, b) is related to zeroing the accelerometers readings, and is performed every time one of the two tooling system components are switched on. The need for setting the accelerometer measurements around zero, every time they switched on, arises from the tool's and/or the machine's table devices could have different orientations in three-dimensional space every time when they are put in the milling machine's spindle or onto the machine's table. Because the accelerometers are of MEMS type, the Earths gravity will act on them, and this will lead to a deviation of the accelerometers readings along the Z-axis with near to the gravity constant. Due to positional imperfections of the MEMS according to the X- and Y-axes, there will also be certain gravity components for these axes as well in the sensors readings. That is why the calibration of the MEMS actually is related to the removing the gravity components from the accelerometers readings along to the each of milling machine axes. The gravity component value for Z-axis can be calculated by the following expression:

$$aZ_{offset} = -\frac{\sum_{i=p}^{q+p} aZ_i}{q}, \qquad (1)$$

where: p - is an integer that denotes the number of initial measures discarded in order to start calibration when the tool has a stable position in the spindle (p=100); q – is an integer that denotes the buffer size (q=1000); aZ_i- is the current acceleration measurement; aZ_{offset} - is a gravity offset of the Z-axis, calculated as mean value of all q measurements done during the calibration procedure.

In order to remove the gravity component from every acceleration aZ_i measured along to the Z-axis during the burnishing process the following equation is used:

$$aZ_i = aZ_i + aZ_{offset}. \qquad (2)$$

The same calibration procedure is applied to the other MEMS unit, which measure accelerations along to the other two axes X and Y of the milling machine (see Fig. 2, b).

3.2. Measured data logging

After the initial calibration procedure is completed the transmitted values of the deforming force and axes acceleration components is concatenated into a comma separated string, which is appended to the previous records within the ASCII-file in the micro SD-card. Data read rate is determined by the MCU, which is part of the deforming tool (see Fig. 2, a). When the values for deforming force and acceleration along to the Z-axis are read by the MCU, it transmits them to the MCU of the second part, which is on the milling

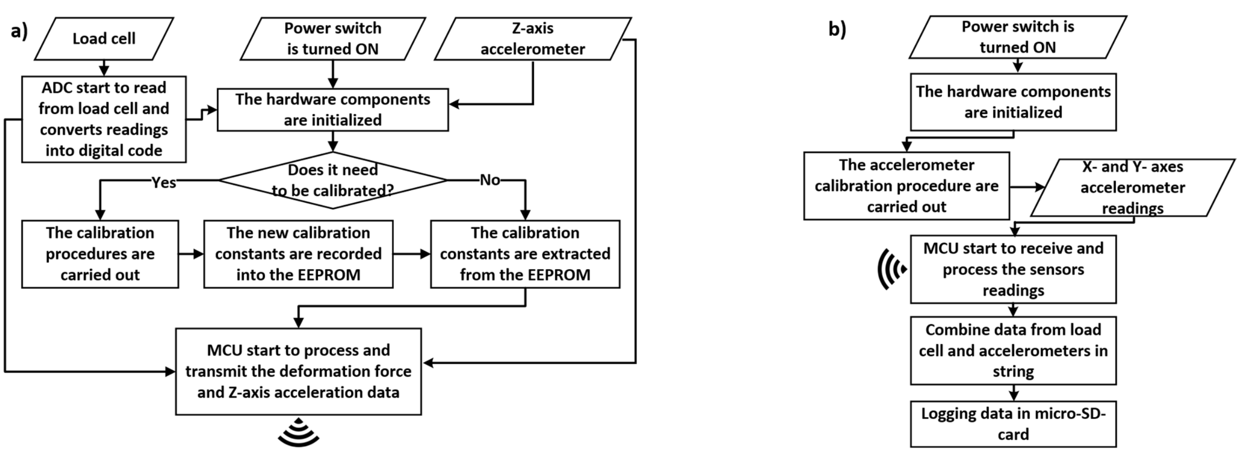


Fig. 4. Operational principle of measuring and data logging tooling system: a) transmitting part; b) receiving and data recording part.

machine table. Every time, when the second MCU receives measured data from the first MCU, a procedure for X and Y-axes acceleration reading from the second MEMS sensor is performed. Therefore, the data read rate depends on the samples per second rate of the used ADC for the load cell, which can reach up to 80 SPS or the time interval between two readings is 12.5 msec.

4. ACTUAL BALL BURNISHING SPEED DETERMINATION USING THE PROPOSED TOOLING SYSTEM

As it was mentioned above, when ball-burnishing operation is used to form regular reliefs on planar surfaces, the needed sine toolpath is deployed in the X-Y plane. As a result, the deforming tool frequently changes its movement direction relative to the CNC-machine axes, which leads to their cyclicall acceleration and deceleration. Therefore, there is a possibility that the certain feedrate set in the milling machine table will not be reached in reality. In order to research the actual speed reached against the programmed feedrate of the deforming tool, an experimental study was conducted.

4.1. A methodology for deforming tool speeds determination using measured accelerations

To determine the actual speed achieved of the deforming tool, two types of RRs toolpaths are programmed using CAMWorks software for six BBs operations based on three different feedrates, as it is shown in Fig. 5.

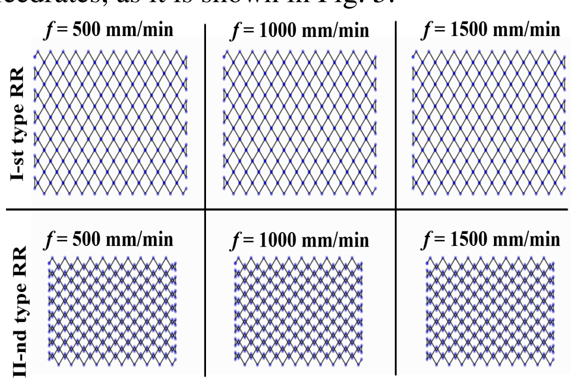


Fig. 5. Diagrams of two types of RR toolpaths, which are performed on three different feedrates.

The experimental study is conducted on a CNC-milling machine type HAAS, TM-1 with the deforming tool described in subsection 2. The burnished specimen is a plate made of 304L stainless steel, which has δ = 3, mm thickness, clamped onto the milling machine table.

Because all of the toolpaths are coplanar with the X-Y plane, only accelerations along to the X and Y-axes measured by MEMS are taken into account. After the acceleration signals are recorded, they are subjected to digital signal processing procedure using the MATLAB software in the following steps:

1. All recorded acceleration signals are subjected to detrend firstly in order for the DC component to be removed. This is done by determining a 4-th order polynomial that fits the signal data, using the MATLAB function "polyfit", which returns the polynomial p(i) coefficients of degree n that is a best fit (based on least-squares approach) for the data in the acceleration signal. The function "polyval" is used to evaluate the polynomial at each *i-th* value. The calculated difference between the signal values and the corresponding evaluated polynomial values gives the approximation of the signal fluctuating around zero.

2. The detrended signal is further subjected to numerical integration using the "cumtrapz" function in MATLAB, which computes an approximation of the cumulative integral of the signal via the trapezoidal rule with constant step between measurements [12]:

$$V_i^{X;Y} = V_{i-1}^{X;Y} + \Delta t \cdot \left((i+1) - i\right) \cdot \left(\frac{a_i^{X;Y} + a_{i+1}^{X;Y}}{2}\right), \quad (3)$$

where: $V_i^{X;Y}$ – is the speed along the X or Y axis n the i-th moment; $V_{i-1}^{X;Y}$ – is the speed along the X or Y axis in the (i-1)-th moment, $a_i^{X;Y}$ - is the acceleration along the X or Y axis in the i-th interval; $a_{i+1}^{X;Y}$ - is the acceleration along the X or Y axis in the (i+1)-th moment; i = 0 .. n–1 is the measurement index, and *n* is the number of measurements recorded; Δt - is the time interval between two adjacent measurements of the axes acceleration.

3. Next, the vectored speed of the ball tool in the XY plane is calculated as vector summation of the numerically integrated X and Y speed signals data, using the following equation:

$$V_i^{XY} = \sqrt{(V_i^X)^2 + (V_i^Y)^2}, \qquad (4)$$

where V_i^X and V_i^Y are determined using the equation (3).

(see Fig. 5), divided by the measured signal time duration t, min of the current BB operation.

- Sr, mm/min is the mean of the whole vectored speed data recorded, calculated by equation (4) using the "mean" function in MATLAB.
- Srp, mm/min is the mean of the detected peaks only in the recorded vectored speed signal, determined using the "findpeaks" function in MATLAB.

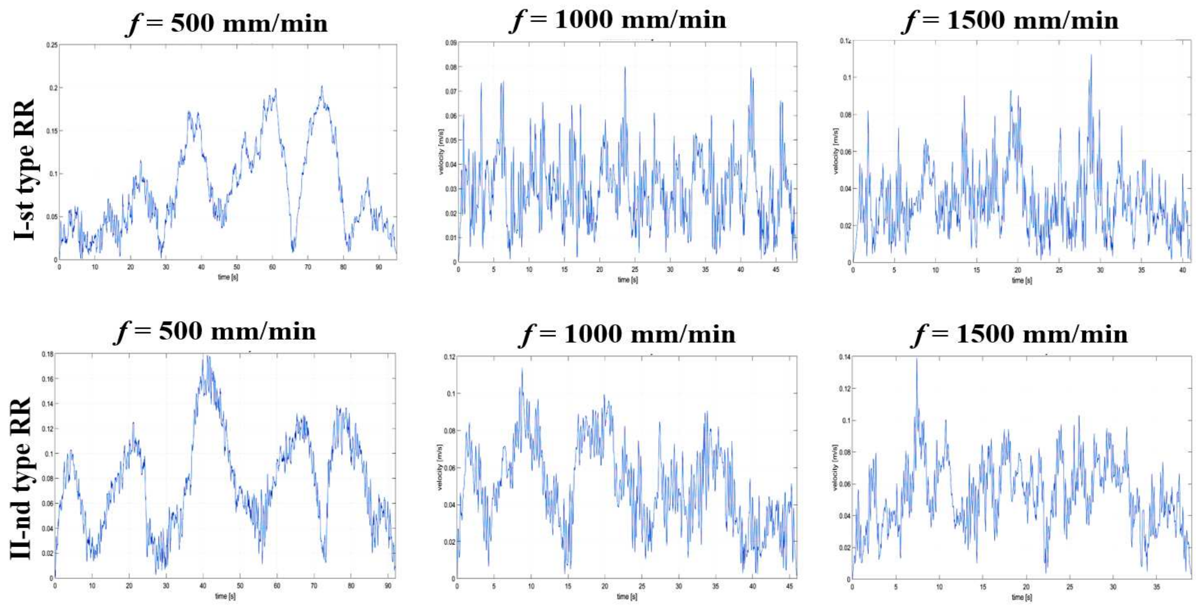


Fig. 6. Vectored speed diagrams derived from axes acceleration integration for two types of RRs and three programmed feedrates, according to the toolpath diagrams shown in Fig. 5.

Table 1

Results for the real deforming tool speeds from the carried out experimental research

Type of RRs pattern	Feedrate programmed in the numerical code for CNC, ***f*, mm/min**	Unfolded length of the toolpath (calculated by CAM) **Lu, mm**	Time duration of the acceleration signals measured **t, min**	Mean speed based on unfolded length, **Sc = Lu / t, mm/min**	Mean of vectored speed measured (whole signal) **Sr, mm/min**	Mean of vectored speed measured (peaks only incl.) **Srp, mm/min**
I	500	807.50	1.583	510.107	426.781	442.845
I	1000	807.50	0.800	1009.375	676.579	803.484
I	1500	807.50	0.683	1182.284	816.678	979.901
II	500	771.02	1.533	502.948	376.720	397.537
II	1000	771.02	0.766	1006.553	680.827	795.481
II	1500	771.02	0.650	1186.184	827.169	1001.509

4. Finally, as a quantity estimation of the vectored speed, based on the acceleration measurements, three mean values of real speeds are calculated (see Table 1):

- Sc, mm/min is the mean speed of the ball tool, calculated by using the unfolded length Lu, mm of the generated by CAM software toolpaths

4.2. Discussion of the obtained results from the experimental investigation conducted

The corresponding speed diagrams, based on the integration of CNC-milling machine axes accelerations, for the two types of RRs and for the three feedrates, according to the toolpaths patterns (see Fig. 5) are shown in Fig. 6. The obtained vectored speed means Sr, mm/min and means of the speed peaks Srp, mm/min are shown in Table 1. The Sc, mm/min speeds are also given in Table 1 as reference. The Sc determined using the unfolded length of the toolpath Lu, mm, derived from the CAM software, and the actual time duration t, min of the BB operations taken from the recorded acceleration signals (see Fig. 6).

From Fig. 6 it can be seen that the vector speeds of the deforming tool, calculated using equation (4), shows significant variability along the toolpath length. Such a behavior was anticipated, due to the toolpath's direction variability which results in one of the machine axes to accelerate at the beginning of a given segment, while the other to decelerate at the same time. The same process is repeated for the next toolpath's segment but the vector speeds magnitude are changed in alternative manner.

The calculated mean speeds Sc (see Table 1) have quite close values to the feedrates set in the NC-code because the variations of the speed in different positions of the toolpath are not taken into account in that calculation. If this variability is accounted for, lower values than the programmed feedrates are obtained. The speed values for Sr and Srp shown in Table 1 confirm the assumption that the real achieved speed of the CNC-milling machine table and/or the deforming tool are significantly smaller than the programmed values of feedrate in NC-code. For example, if the programmed feedrates f from Table 1 are compared with the means of vectored speed Sr values it can be seen that the difference varies between 14.6 and 45.5% for RRs of I-st type, and between 24.7 and 44.9% for RRs of II-nd type. It is noteworthy that as the programed feedrate increases, the percentage difference between them and the actual mean speed values also increases for both types of the reliefs. The dependencies are quite similar if mean values of vectored speed Srp, determined only by peaks of the speeds are used instead. The only difference is that the percentage differences are smaller. That peculiarity of the CNC-machine tools should be taken into account when ball-burnishing operation is planned, because the surface layer's plastic deformation speed is closely related with real speed reached by the deforming tool, and it could significantly affect the operational characteristics of the burnished surface, including its tribological behavior.

5. CONCLUSION

In the present work, the design and operation principle of an advanced tooling system for BB of planar surfaces, performed on CNC-milling machine is presented. It gives the opportunity to measure and log the data simultaneously for two of the main regime parameters of the operation – deforming force and actual axes accelerations during the operation, based on low coast and easy-to-use IoT components. Based on its measuring capabilities an experimental investigation are carried out to determine the difference between programmed and real axes speed achieved. As a result, it is found that the real speed that the milling machine can reach is lower - between 15 and 45% than that of the programmed feedrate values in the NC-code.

The present research should not be considered as exhaustive work that covers all matters related to the determination of the actually achievable deforming tool speed, but only as a first step in this aspect of the application of the BB process. Our future work will be focused on testing different sensors for acceleration measurements and algorithms for more precise numerical integration of measured data.

6. ACKNOWLEDGEMENTS

The present work is funded by Bulgarian National Science Fund (BNSF), under grant contract № KP-06-N57/6, entitled "Theoretical and experimental research of models and algorithms for formation and control of specific relief textures on different types of functional surfaces" for which the authors are sincerely grateful.

7. REFERENCES

[1] C. Ramnarayan, Advanced Thermally Assisted Surface Engineering Processes. Mumbai, India: Springer Science & Business Media, 2007. [Online]. Available: https://books.google.bg/books?id=gonhBwAA

QBAJ&printsec=frontcover#v=onepage&q&f=false (accessed Feb. 09, 2024)

[2] A. Raza and S. Kumar, "A critical review of tool design in burnishing process," Tribol. Int., vol. 174, p. 107717, Oct. 2022, doi: 10.1016/J.TRIBOINT.2022.107717.

[3] Шнейдер Ю.Г., "Эксплуатационные свойства деталей с регулярным микрорельефом (Performance characteristics of parts with regular microrelief)," 2001. https://books.ifmo.ru/file/pdf/147.pdf (accessed Jan. 12, 2024).

[4] G. Nagîţ, L. Slătineanu, O. Dodun, M. I. Rîpanu, and A. M. Mihalache, "Surface layer microhardness and roughness after applying a vibroburnishing process," J. Mater. Res. Technol., vol. 8, no. 5, pp. 4333–4346, 2019, doi: 10.1016/j.jmrt.2019.07.044.

[5] V. Dzyura, P. Maruschak, H. Kozbur, P. Kryvyi, and O. Prentkovskis, "Determining Optimal Parameters of Grooves of Partially Regular Microrelief Formed on End Faces of Rotary Bodies," Smart Sustain. Manuf. Syst., vol. 5, no. 1, pp. 18–29, Jan. 2021, doi: 10.1520/SSMS20200057.

[6] G. Gomez-Gras, J. A. Travieso-Rodríguez, H. A. González-Rojas, A. Napoles-Alberro, F. Carrillo, and G. Dessein, "Ball-burnishing vibration-assisted process," 2014.

[7] S. D. Slavov, D. M. Dimitrov, and M. I. Konsulova-Bakalova, "Advances in burnishing technology," in Advanced Machining and Finishing, Elsevier, 2021, pp. 481–525. doi: 10.1016/B978-0-12-817452-4.00002-6.

[8] S. Attabi, A. Himour, L. Laouar, and A. Motallebzadeh, "Surface Integrity of Ball Burnished 316L Stainless Steel," Stainl. Steels [Working Title], Jan. 2022, doi: 10.5772/INTECHOPEN.101782.

[9] S. Slavov, "An Algorithm for Generating Optimal Toolpaths for CNC Based Ball-Burnishing Process of Planar Surfaces," in Advances in Intelligent Systems and Computing, vol. 680, 2018, pp. 365–375. doi: 10.1007/978-3-319-68324-9_40.

[10] S.D. Slavov and I.V. Iliev, "Design and FEM static analysis of an instrument for surface plastic deformation of non-planar functional surfaces of machine parts," Fiability Durab., vol. 1, no. 2, pp. 3–9, [Online]. Available: https://www.utgjiu.ro/rev_mec/mecanica/pdf/2016-02/01_STOYAN%20SLAVOV,%20ILIYAN%20ILIEV%20-%20DESIGN%20AND%20FEM%20STATIC%20ANALYSIS%20OF%20AN%20INSTRUMENT%20FOR.....pdf (accessed Feb. 27, 2024).

[11] S. Slavov, S., and O. Markov, "A tool for ball burnishing with ability for wire and wireless monitoring of the deforming force values," ACTA Tech. NAPOCENSIS - Ser. Appl. Math. Mech. Eng., vol. 65, no. 4S, Mar. 2023,Available: https://atna-mam.utcluj.ro/index.php/Acta/article/view/2066 . (accessed Jan. 18, 2024).

[12] MathWorks Help center: Numerical Integration and Differentiation. Available: https://www.mathworks.com/help/matlab/numerical-integration-and-differentiation.html (accessed Apr. 18, 2024).

O CERCETARE EXPERIMENTALĂ A VITEZEI REALE ATINSE LA PRELUCRAREA RELIEFURILOR REGULARE FOLOSIND UN INSTRUMENT AVANSAT DE DEFORMARE PENTRU LUSTRUIRE CU BILE

Rezumat: Lucrarea actuală descrie proiectarea și principiul de funcționare al unui sistem de scule avansate care funcționează cu mașini de frezat cu control numeric computerizat (CNC), care este utilizat pentru crearea unor modele de suprafață specifice distribuite regulat pe suprafețe plane, bazate pe lustruire cu bile (BB). Sistemul de scule propus în lucrarea curentă are capabilități de măsurare a forței de deformare și a accelerațiilor de-a lungul axelor X, Y și Z în timpul funcționării BB. Valorile măsurate de la senzorii sculelor pot fi transmise fără fir către sistemul de achiziție de date, unde sunt combinate cu accelerațiile măsurate de-a lungul axelor X și Y ale mașinii, astfel încât toate datele să fie stocate pe un card de memorie SD pentru continuarea analizeI. Se efectuează o cercetare experimentală pentru a determina vitezele reale atinse de mașina CNC folosind sistemul de scule avansate propus. Rezultatele obţinute sunt prezentate și discutate la sfârșitul lucrării.

Stoyan SLAVOV, Prof., PhD, Eng., Technical University of Varna, Head of Department of Manufacturing Technologies and Machine Tools, sdslavov@tu-varna.bg, 1 Studentska Str., 9010 Varna, Bulgaria, Phone: +359 52 383 690

Georgi VALCHEV, PhD student, Eng., Technical University of Varna, Department of Manufacturing Technologies and Machine Tools, georgi.valchev@tu-varna.bg, 1 Studentska Str., 9010 Varna, Bulgaria

Oleksandr MARKOV, PhD student, Eng., Technical University of Varna, Department of Manufacturing Technologies and Machine Tools, o.markov@tu-varna.bg, 1 Studentska Str., 9010 Varna, Bulgaria