Determination of the working gap and optimal machining parameters for magnetic assisted ball burnishing

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ABSTRACT

This paper presents the results of various experimental analysis regarding a permanent Magnetic Assisted Ball Burnishing (MABB) tool. This type is a special tool using the magnetic field to produce the necessary force for burnishing, it is applicable especially to rolling flat and 3D harmonic surfaces. For the correct operation of this special kind of tool, the set up for optimal distance between the tool and workpiece was introduced also taking into the account the measured rolling force (F_z), which occurs between the tool and workpiece because the magnetic force pulls the rolling balls on a cone which is located at the end of the tool. In this paper the optimisation of the process parameters for burnishing of C45 normalized pre-machined steel is also presented. To determine the dominant machining parameters the resulted surface roughness and the tribological parameters were also anaysed. The evaluation was completed by advanced measuring and IT equipment.

1. Introduction

"One of the most competent surface engineering methods i.e. mechanical treatment, is the burnishing process" [1]. There are several type of burnishing, like roller burnishing [2], ball burnishing [2] or diamond burnishing [3]. There are also some technologies which are similar to them, for example shot peening [4] and not to mention the special processes like laser-assisted burnishing which is able to burnish high hardness (45-60 HRC) metals [5].

Nowadays the ball burnishing processes have become more accepted as a post machining, metal finishing operation [6], the main aim of conventional ball or roller burnishing is to achieve high-quality surfaces. All surfaces of mechanical parts can be considered as valleys and peaks. During the process one or more balls makes plastic deformation on the surface layer. In the case, if this stress is higher than yield strength of the material, the material near the surface starts to flow [7, 8]. In this state, there is a possibility that it may lead to plastic deformation of higher asperities contacted, having the modest effect on the surface quality. It may cause severe wearing behavior which thanks to the burnishing processes increase the hardness and decrease the roughness of the machined surface [1].

As the balls moves across the surface of workpiece, the peaks of surface are pressed down into the material and it flows into the valleys between the peaks as it is presented in Fig. 1. [7, 8, 9].
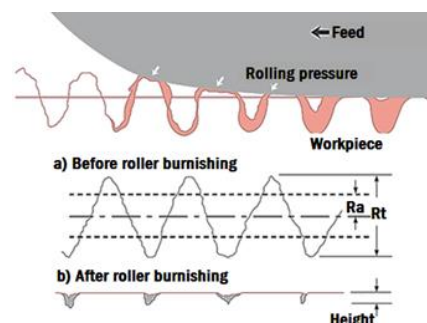

Fig. 1. Evolution of surface by burnishing [7]

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Several studies have investigated the effect of burnishing on the workpiece properties (e.g. increasing the residual stress, hardness, corrosion and wear resistance further to enhance the fatigue life and surface quality) [10, 11, 12]. Because its's simplicity and economical effectiveness, the burnishing is a widely used cold treatment/machining process. The type of burnishing process depends on the form of the workpiece (e.g. flat or cylindrical). In the paper a newly designed and introduced flat-surface ball burnishing tool was examined. The burnishing of flat or 3D harmonic surfaces needs special tools and/or equipment (e.g. hydraulic hose and pump) e.g. F. Gharbi, S. Sghaier and T. Benameure designed a tool, which consist of four burnishing tools which are adapted in a special tool holders (Fig. 2.) [13].
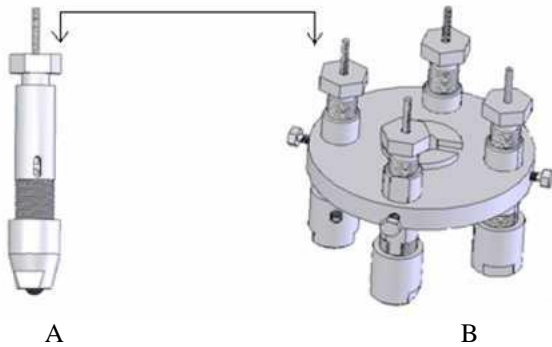

Fig. 2. (A) The simple ball burnishing tool and the (B) tool holder with four ball burnishing tools [13]

The main problem with most of the burnishing tools (such as in Fig.2.) is their applicability in a CNC machine because it is difficult to place them into the tool magazine, in Table 1. the advantages and drawbacks of various burnishing technologies are compared.

Table 1.
Cold metal working surface improvement technologies

Technology	Advantages	Drawbacks
Roller burnishing [2]	cheap tool	only cylindrical workpiece
Ball burnishing [3]	cylindrical and flat workpiece	expensive tool
Diamond burnishing [4]	hard workpiece	rigid tool
Shot peening [5]	3D contoured surfaces	required special equipment

Considering drawbacks of expensive and complicated construction, the authors designed a novel Magnetic Assisted Ball Burnishing (MABB) tool. During the design process, the Magnetism Aided Machining or Magnetic Assisted Machining (MAM) technologies were investigated [14, 15, 16, 17, 18], which are relatively novel industrial machining processes. The MAM technologies are mainly suitable for finishing and surface improvements. The MABB tool was developed to reduce the surfaces

roughness increasing the surface hardness and deburring the edge of flat (in some cases even 3D harmonic surfaces) metal parts. The magnetic force makes this process simple, productive and environmental friendly, it is generated by the magnetic field between the workpiece and the tool, so, it is so important to set up the right tool-workpiece distance to ensure the optimal rolling pressure [19].

Several machining parameters, namely burnishing speed, feed rate, force, number of burnishing passes, workpiece material and hardness, ball material, ball size, number of balls and lubricant have to be considered to define an effective and efficient burnishing process [20, 21].

A.M. Hassan and A.S. Al-Bsharat presented in their research that the burnishing forces and the number of tool passes are predominant parameters that have effect on the surface roughness of the workpiece during the burnishing process [22].

Taking into the account that the introduced ball burnishing technology is a novel solution, it has to be positioned among other techniques having similar manufacturing aims (e.g. as in Table 1.), moreover it has to be characterized and it's capabilities have to be qualified by various measuerements. The analyzed ball burnishing technology improves the tribological features of the machined surface significantly. The most frequently used charcterization features of a surface from triboloical point of view are the R_{sk} and R_{ku} roughness parameters, consequently, these quantification measures were used to describe the effectiveness of the proposed ball burnishing soultion. The experiments proved also that a more favourable solution is the application of the rotating dynamometer instead of a multicomponent dynanometer and it can be used for measuring the burnishing force and also in the optimisation of the working gap and the technological parameters, too.

2. Magnetic assisted ball burnishing tool

The novel MABB tool contains four magnetizable bearing balls and the magnetic force pulls these balls to a cone which is located at the end of tool and this construction results in the necessary F_z rolling force (F_z in Fig. 3.).
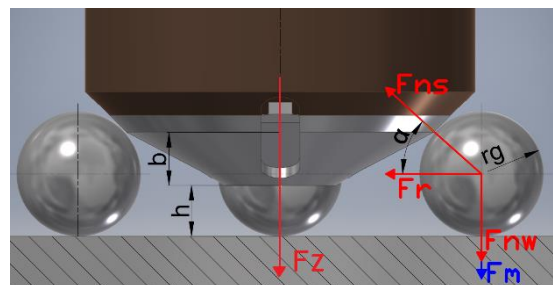

Fig. 3. The generated force during ball burnishing

The first generation of MABB tools are working with an electromagnet (Fig. 4.). The constructions' main advantages are the adjustable magnetic force which gives less importance to the gap distance. But this adjustable

function causes problem in the usability, because it requires electric cables feed to the tool during machining, so it is not advantageous to a modern CNC machine. Furthermore, the electromagnetic coil heats up during machining and, as a result, decreases the magnetic field strength [23].
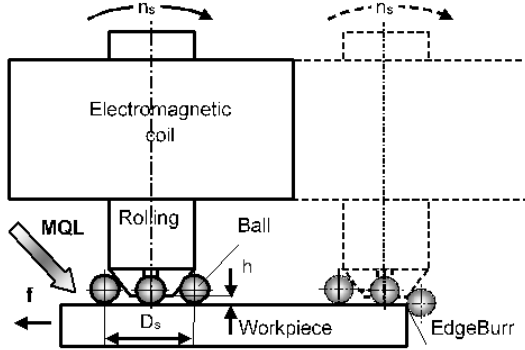

Fig. 4. Concept of the electro MABB tool [23]

The new MABB tool works with NdFeB permanent magnet instead of the electromagnet (Fig. 5.). Thanks to the permanent magnet design, the tool can be placed into the tool magazine, removing edge burr and following the topology of surface.

In a recent study M.M. El-Khabeery and M.H. El-Axir they identified some of the main effects of the burnishing. Their results are useful and contains essential statements (e.g. the burnishing speed should not exceed about 120 m/min to obtain high surface quality), but as it was mentioned also the tool gap has great significance and so it must be an optimum value [24]. Many further research studies have been conducted to investigate the effects of burnishing feed, speed and force on surface roughness during burnishing process [25, 26, 27].
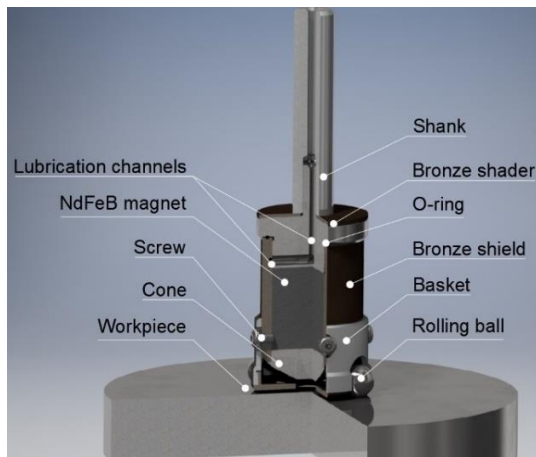

Fig. 5. Parts of permanent MABB tool

High burnishing force is required to achieve low roughness. Because the introduced MABB tool is a novel solution, so, the optimal working gap distance resulting in the highest burnishing force is unknown. This parameter was determined by calculation (Paragraph 3) and

experiments (Paragraph 4.), too. The experiments consisted in two parts. Since the centrifugal force on the balls decreases the pressure of them to the surface, so, the first test was performaed by a standing tool, (first part in Paragraph 4.) and in the second paert of the analysis the tool was rotating (second part in Paragraph 4.). The search for the optimal machining parameters were done applying the classical Taguchi experimental design method using the already predetermined optimal working gap (described in Paragraph 5.).

3. Determination of working gap by calculation

The optimum working gap (h) between the tool and workpiece can be determined by calculation and experiments, too. The tool geometrical parameters are: ballradius (r_g=8 mm) and cone height (b=5 mm) so they can be used in the equations (1) and (2) in relation to Fig. 3. vectors:

$$h = r_g \cdot (sin\alpha + 1) - b \tag{1}$$

$$F_{nw} = F_r \cdot tan\,\alpha \tag{2}$$

where F_{nw} the burnishing force per ball and F_r is the radial magnetic attraction force. The Fig. 3 also represents the vectors of the resulting force of F_r (F_{ns}) and the attraction force of workpiece (F_m), but the recent is negligible.

The equalization of (1) and (2):

$$F_{nw} = F_r \cdot tan \cdot \left(arcsin \left(\left(\frac{h+b}{r_g} \right) - 1 \right) \right) \tag{3}$$

In equation (3) the F_r is constant, because there is no change in the permeability of the ball and the gradient of magnetic field during the rolling. The calculations are initiated with h=4 mm gap and tested up to h=12 mm.
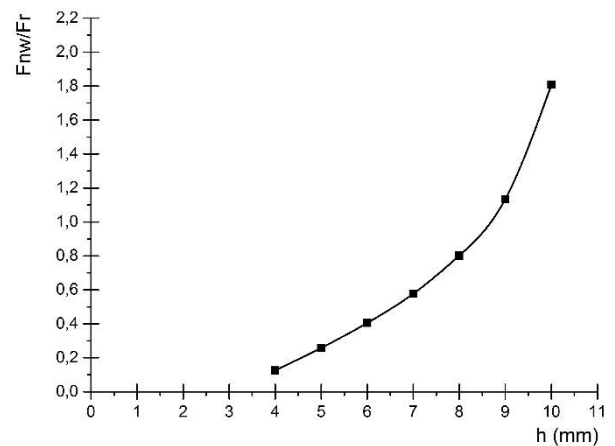

Fig.6. The relationship between h and F_{nw}/F_r by calculations

Under the h=4 mm gap the balls can fly away, because the balls reach the tool edge which made from bronze and they cannot be affected by the magnetic field. Reaching the

h=11mm gap and the α=90° there is no solution for the tangent calculation. Using the equations a graph representing the relation beween *h* and F_{nw}/F_r is determined (Fig. 6.).

According to the calculation, the optimum gap distance for the highest burnishing force is about h=10mm.

4. Determinning of the working gap by experiment

Results of calculations may differ from the reality, therefore the determination of the optimal gap is carried out by experiments, too. For the experiments a CNC milling machine and a KISTLER Type 9125A24A2 force and torque measuring instrument were used (Fig. 7.) during set-up and machining processes.

Fig. 7. KISTLER rotating dynamometer with end mill [28]

The measuring took 100sec while the sampling rate was 500Hz. The measuring range of F_z was set up between -400–700N.

To avoid accidents, as a first step, the tool was tested in a standing position (without the main rotating movement) and after knowing the optimum gap, the rolling force was measured continuously while the tool was rotating.

4.1. Standing tool

The results of the calculations were used for the experiments, so the starting position with standing balls was the maximum of *h*=11 mm gap and it was tested down to *h*=4 mm. The measurement arrangement is shown in Fig. 8.

The measurement started in h=14 mm, without balls, then the balls were placed into their positions and the tool moved away from the surface with 1mm steps. The result of the measurements are shown in Fig. 9.
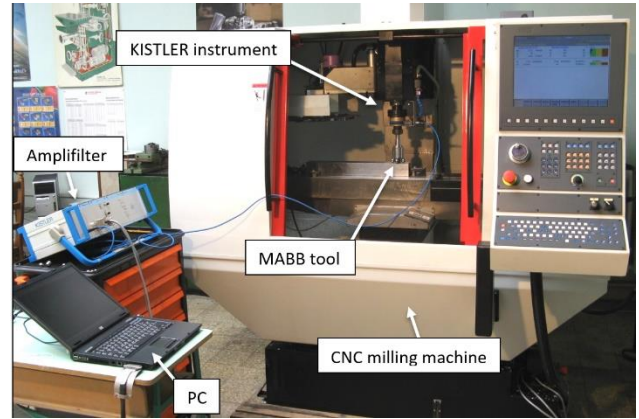

Fig. 8. Experimental setup of the force measuring

As represented in Fig. 9. without balls, the tool attracts the workpiece, consequently, this is the reason for the small negative F_z force. After placing the balls into the workspace, the tool began pushing the workpiece through the balls. As it is represented in Fig. 9., the maximum force arose with *h* = 10mm gap and under *h* = 6mm the F_z force will be again negative. This means that here the tool started to attract again the workpiece by the balls and also by the cone of the tool, too.
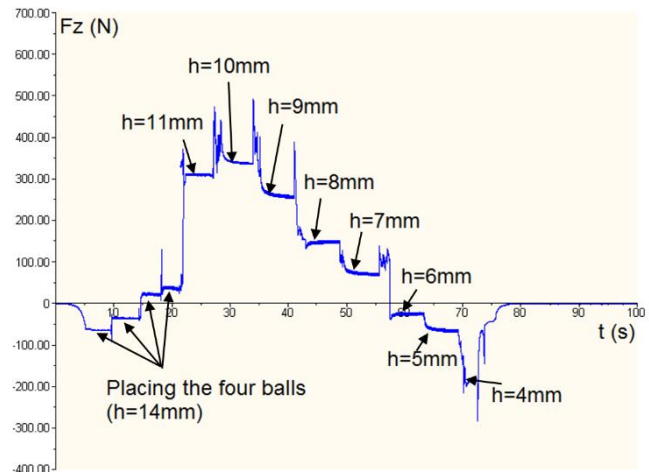

Fig. 9.The magnetic force depending on the tool distance

According to the expectations and the calculation, the maximal force (F_z=350N) was measured at h=10mm. Because there are four balls, force of 87,5N per ball with standing tool is resulted.

4.2.Rotating tool

The main problem with a rotation is that it increases the centrifugal force which can significantly reduce the burnishing force, moreover, under special conditions the balls can fly away. In order to avoid it, the rolling force was measured during increasing revolution, from 0 to 1400 rev/min. The measured F_z values are summarized in Fig. 10.
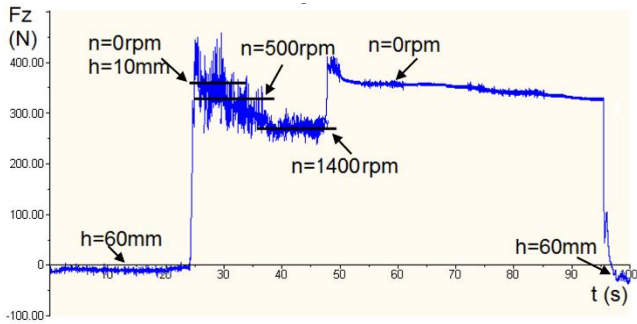
Fig. 10. Magnetic force depending on the revolution speed

As the Fig. 10. shows the effect of increasing revolution, that resulted in decrease of the rolling force from 350N to 260N, it shows that the force was decreased by 25%. *This decline is not a very significant value* and in the practice experts never use higher revolution than 1400rev/min, because the higher revolution negatively affects the quality of the surface, too [24]. *Consequently, the tool can be safely used until 1400 rev/min.* In practice, the best revolution range is between 150-500 rev/min [20].

5. Optimisation of machining by experiments

The influence of roller burnishing parameters on the machined surface roughness was experimentally studied applying gap set-ups around the the previously determined, optimal value. Beside the gap distance the rolling speed (v_r) and feed (v_f) technological parameters have the main effects on surface roughness. In the consciousness of this the aim is to find optimal values for v_r and v_f. The experimental details and procedures adopted to carry out the machining parameter's optimisation are summarized in the next paragraph.

5.1. Experimental circumstances

Testing sample was a C45-type hot rolled steel. The burnishing tool diameter was D=43mm, and the hardened (HRC60) bearing balls' diameters were d=Ø16mm (Fig. 11.).

The burnishing processes, as most of the all cold forming techniques, requires lubricant. Many types of oil can be used, in this experiment the Minimum Quantity Lubrication (MQL) system with 20 °E synthetic oil was applied [29].

Fig. 11. The permanent MABB tool during machining

5.2. Design of experiment (DoE)

The primary goal was to determine ideas about effects of technological parameters on the burnished surfaces. The design of the experiments (DoE) provides suggestions how to efficiently perform experimentation to evaluate the effect of the process factors on the outcomes of the process.

The Taguchi DoE technique is a powerful tool for engineering design method and its dominant advantage is to remarkably reduce the number of experiments, so, it reduces the experimental cost and time by the use of an orthogonal array [30].

Table 2
Burnishing factors and levels

	Burnishing factor	Level		
		1	2	3
A	Burnishing speed (v_r) [m/min]	20	40	60
B	Feed (v_f) [mm/min]	25	50	75
C	Tool gap (h) [mm]	8,5	11,5	10
D	Premachined surface quality (R_a) [µm]	0,950	0,672	1,105

Three different categories of performance characteristics are usually used to calculate the SNR (Single to Noise ratio), depending whether in the applied Taguchi experimental design method for the optimisation target the lower (value) is the better, the higher is the better and the nominal is the better [31]. In the presented case, the higher is the better characteristic was used, because the process outcome to be evaluated was the improvement of the surface roughness after ball burnishing.

The corresponding SNR is given by (4)

$$SNR = -10 \cdot \lg \frac{1}{n} \sum \frac{1}{y_{ij}{}^2} \qquad (4)$$

where y_{ij} is the measured experimental result and *n* is number of the experiments [31].

Using the calculated SNR, the effects of the process factors on the improvement of surface roughness by the MABB were evaluated. The selected burnishing factors and their levels are listed in Table 2. In the practice and as determined above, the best revolution range is between 150-500 rev/min so, taking into consideration the tool diameter, the burnishing speed were 20, 40 and 60 m/min. Based on this logic, set-up values for the feed were 25, 50 and 75 mm/min.

In the practice, the burnishing process is applied e.g. after milling, so the authors previously milled the workpiece by three feed parameters (since, feed has the most determinant effect on the resulted surface roughtness): 100, 200 and 300 mm/min and these feed parameters have resulted in 0,672; 0,950 and 1,105µm for the Ra surface roughness. The cutting speed was set-up to 120m/min and the cutting depth was 1mm in milling.

5.3. Experimental results

The optimal burnishing parameters studies were carried out as per the standard orthogonal array L9 (3^4). The experimental results were analyzed through MINITAB 17 software tool that serves also with the related DoE table. The surface roughness, burnishing force and tribological features were studied by Origin Pro data analysis and graphical software.

The experiments guide were specified according to

Table 2 and then the surface roughness and burnishing force were evaluated by Taguchi method (Table 3.).

Table 3
Orthogonal array table for the designed experiments

No.	Burnishing factor			
	A	B	C	D
1	20	25	8,5	0,950
2	20	50	11,5	0,672
3	20	75	10,0	1,105
4	40	25	11,5	1,105
5	40	50	10,0	0,950
6	40	75	8,5	0,672
7	60	25	10,0	0,672
8	60	50	8,5	1,105
9	60	75	11,5	0,950

For evaluation (surface roughness and burnishing force) a surface roughness measuring equpiment (MITUTOYO Formtracer SV-C3000) was used for pre-machined as well as for burnished surfaces. Each surface was measured three times and the average of them are presented in the Table 4. The comparison of the pre-machined and burnished surfaces are shows in Fig. 12.

The Fig. 12. represents that after ball burnishing the peaks are pressed down while the valleys are filled up according to thematerial flow, but some of the valley were not filled up because they are too deep. These remaining valleys not harmful because these are function as oil pockets which results better sliding properties.

Table 4
Burnishing factors and levels

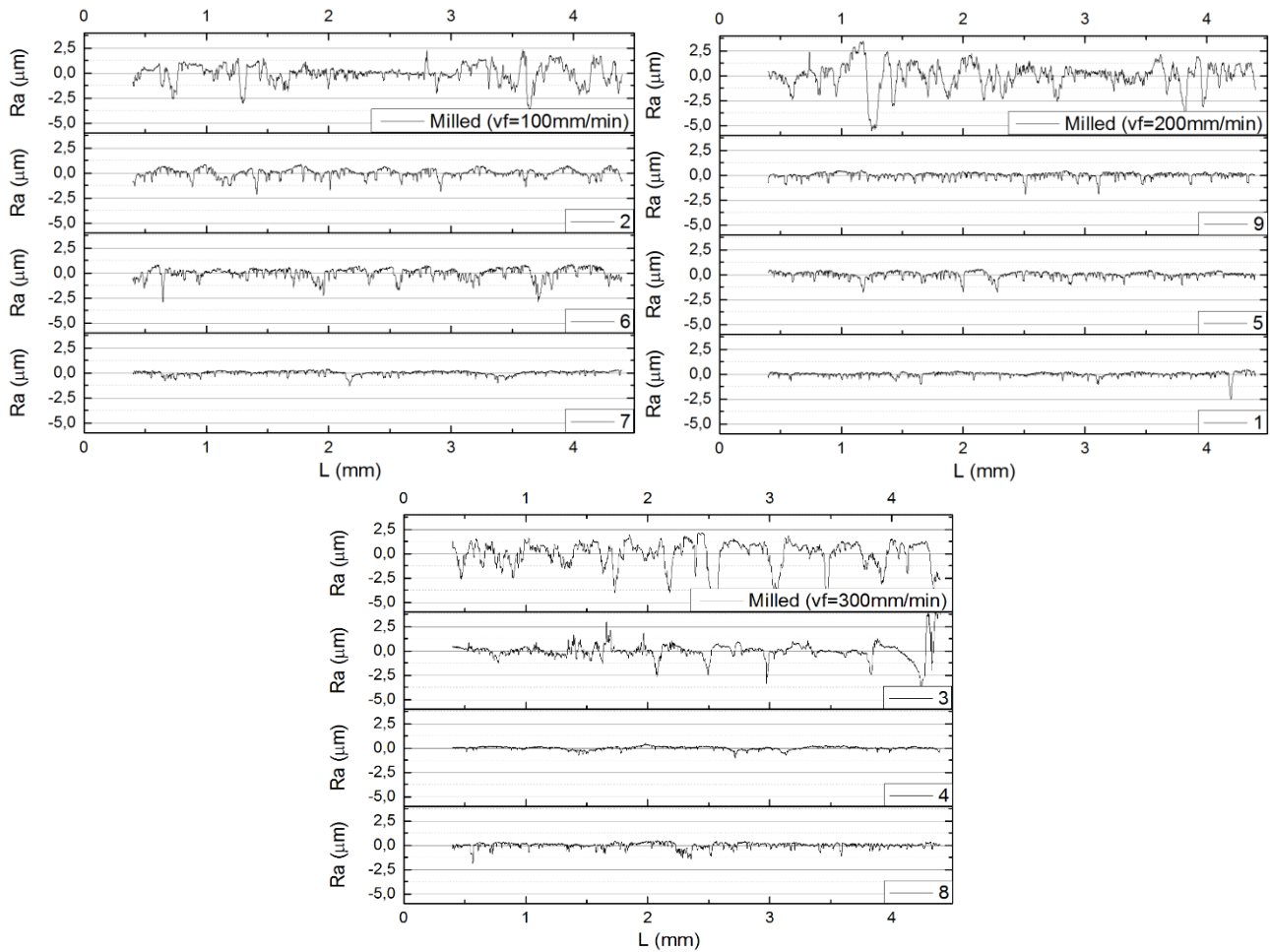| No	Ra before burnishing (µm)	Ra after burnishing (µm)	Improvement of Ra (µm)	*Singal to Noise (S/N)* ratio for surface roughness (dB)	Burnishing force (N)	*Singal to Noise (S/N)* ratio for burnishing force (dB)
1	0,950	0,159	0,791	-15,9721	234,8	47,4140
2	0,672	0,351	0,321	-9,0939	227,3	47,1320
3	1,105	0,580	0,525	-4,7314	266,0	48,4976
4	1,105	0,127	0,978	-17,9239	228,2	47,1663
5	0,950	0,256	0,694	-11,8352	266,5	48,5139
6	0,672	0,445	0,227	-7,0328	247,4	47,8680
7	0,672	0,159	0,513	-15,9721	248,0	47,8890
8	1,105	0,235	0,87	-12,5786	229,0	47,1967
9	0,950	0,204	0,746	-13,8074	205,5	46,2562

Fig. 12. Comparison of the pre-machined (with three different machining feed) and burnished surface roughness profiles measured three times

Table 5. shows the influence of the burnishing factor. This response table helps to get more information about the process under investigation since the highest delta value appoints the most influential factor. According to the results represented in this table, for surface roughness reduction the order of influence of the factors is: 1. the burnishing feed, 2. burnishing speed, 3. pre-machined surface quality and 4. tool-workpiece gap.

Table 5
Influence of burnishing factor (depending on surface roughness)

Factor	Level			Delta	Rank
	1	2	3		
A	-9,932	-12,264	-14,119	4,187	2
B	-16,623	-11,169	-8,524	8,099	1
C	-11,861	-10,846	-13,608	2,762	4
D	-10,700	-13,872	-11,745	3,172	3

The main effects of the burnishing factors on the surface roughness improvement after MABB processing are shown in Fig. 13. In the Taguchi method, higher SNR for the experimental results is desirable and the optimal conditions can be easily determined by selecting the combination of the maximal SNR in each factor.

As shown in Fig. 13. the determined optimal condition is a combination of A1-B3-C2-D1 (v_r: 20 m/min - v_f: 75 mm/min - h: 11,5 mm - R_a: 0,950 μm) (Table 2.). This optimal combination was not tested in the previous experiments because the combination was not matched in Table 3.
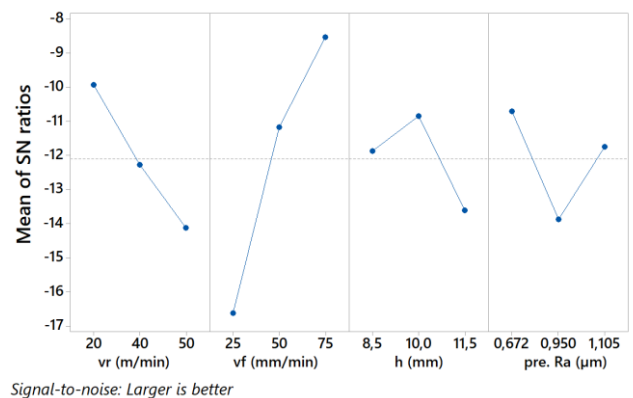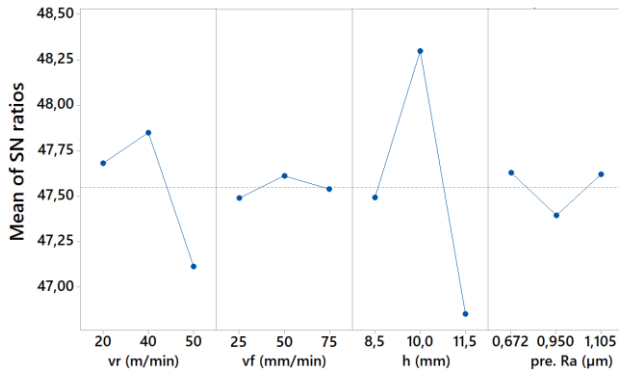

Fig. 13. Analysis of main effects of burnishing factor

The next response table (Table 6.) shows the most influenting factor for burnishing force improvement.

Table 6
Influence of burnishing factor (depending on burnishing force)

Factor	Level			Delta	Rank
	1	2	3		
A	47,68	47,85	47,11	0,74	2
B	47,49	47,61	47,54	0,12	4
C	47,49	48,30	46,85	1,45	1
D	47,63	47,39	47,62	0,23	3

In this case the most influencing factor for surface reduction in sequence: 1. tool-workpiece gap, 2. burnishing speed, 3. pre-machined surface quality and 4. burnishing feed.

Fig. 14. Analysis of main effects of burnishing factor

The main effect of the burnishing factors on the burnishing force is shown in Fig. 14., the determined optimal conditions are a combination of A2-B2-C2-D3 (v_r: 40 m/min - v_f: 50 mm/min - h: 11,5 mm - R_a: 1,105 µm), that was not defined in Table 3.

6.2. Burnishing force

In order to determine the (F_z) burnishing force during the burnishing tests it was measured by the previously described force and torque measuring instruments. This measurement is important because it will help to get know the tool usability for 3D harmonic surfaces. The Fig. 15. shows trends of burnishing forces during the experiments.

The burnishing force highly depends on the tool-workpiece gap (h), burnishing speed (v_r) and even the feed (v_f) (Fig. 15.) which is proved by the results of Table 6, too.
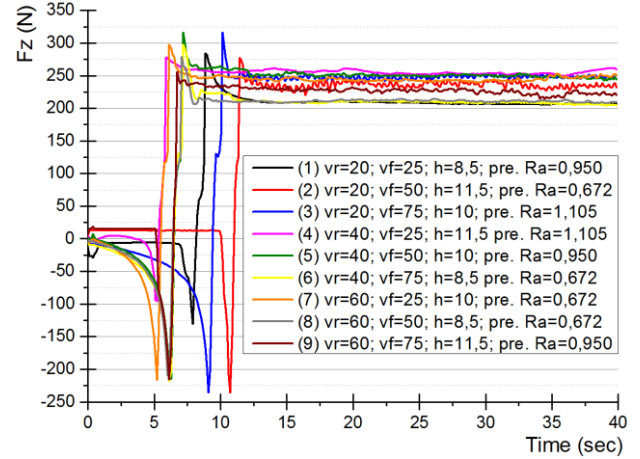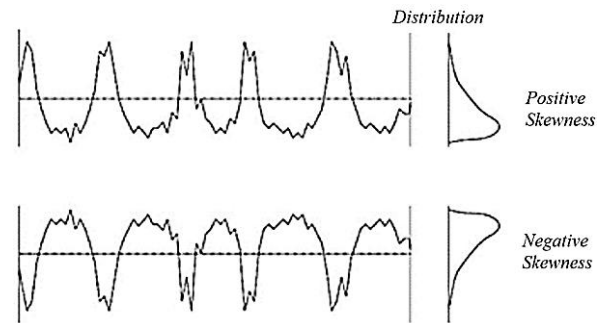
Fig. 15. Burnishing force measurements

6.3. Analysis of tribological aspects

In industrial practice the surface topography is one of the most critical factors and important indicators especially for the performance of high precision components. Some symptoms can be used to control the manufacturing process: changes in the surface texture, changes in the manufacturing process like machine tool vibration or tool wear. Furthermore, it helps to interpret functional properties of macro, micro and nanogeometry which directly impact on tribological system [32]. There are some tribology related roughness parameters such as R_{sk} and R_{ku} which strongly depend on the method of the manufacturing process.

The skewness (R_{sk}) is a measure of the symmetry of the profile about the mean line, giving information on asymmetrical profiles for surfaces with the same values of R_a and R_{ms}. Negative values of R_{sk} indicate a predominance of troughs, while positive ones are observed for surfaces with peaks (Fig. 16.) [33].

Fig. 16. Profile types of R_{sk} [33]

The Kurtosis (R_{ku}) is a measure of the sharpness of the profile about the mean line that provides information on the distribution of spikes above and below the mean line. Thus, spiky surfaces will have a high kurtosis value ($R_{ku} > 3$) and bumpy surfaces a low value ($R_{ku} < 3$) (Fig. 17.) [33].
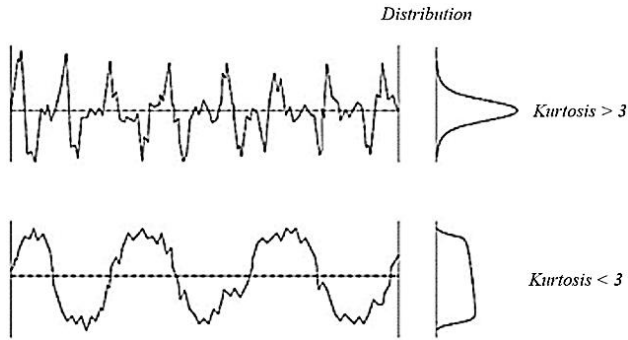
Fig. 17. Profile types of R_{ku} [33]

The statistical index numbers of machined surface roughness are defined by the so-called topological map (Fig. 18.).
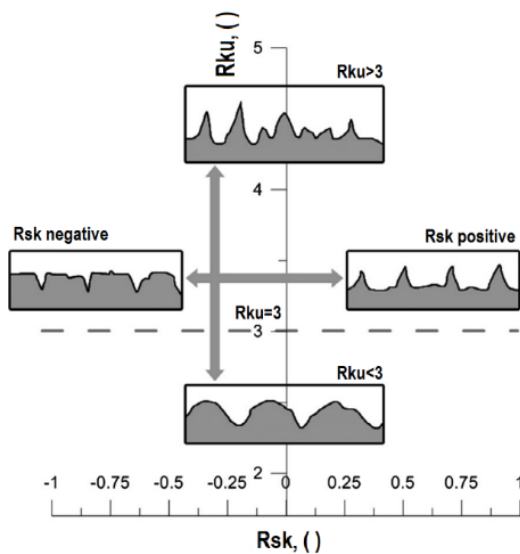

Fig. 18. Graphical representation of R_{sk} and R_{ku} topological map [34]

On the topological map in Fig. 19. the resulted R_{sk} and R_{ku} pair values of the surfaces machined with different manufacturing technologies can be seen [35].

The difference between these groups explains why surfaces machined with different technologies behave differently during operation. It is very important that only those technologies can be placed in the Fig. 19 which can create appropriate surface in tribological aspect. Therefore, technologies such as polishing or lapping cannot be placed because they lead to the stick-slip efect.

One of the aims of the paper is to place the introduced MABB technology on the classical topological map in order to determine also it's position for various of applications (Fig. 20.).

Burnishing process is capable for improving the resistance to wear, corrosion and oxidation. Furthermore the burnishing process helps to reduce friction up to a critical level, beyond that, cracks are initiated and the friction is increasing [37]. The tribological behavior of technological surfaces are related to the micro-geometry of

surfaces. It was observed that surfaces with better wear resistance had negative R_{sk} and under 3 R_{ku} values. The friction is the smallest in those places where R_{sk} was the lowest [37].
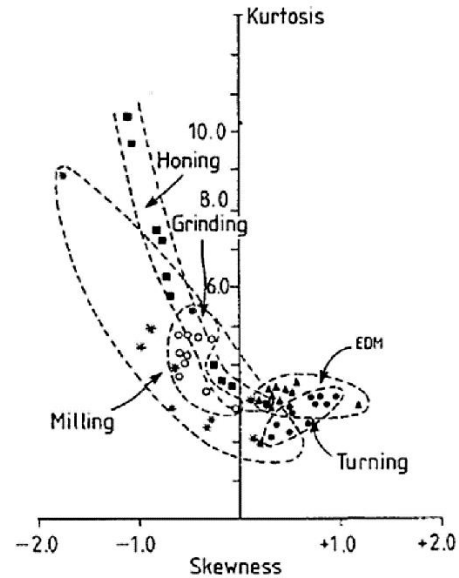

Fig. 19. R_{sk} and R_{ku} topological map of surfaces machined with different manufacturing technologies [36]

Fig. 20. shows the topological map of MABB technologies where the red zone is the milling area (before burninshing) and the black is the area after burnishing. So, the surfaces before the MABB machining are the black points and after MABB the red points, consequently, Fig. 20. represents the movement of the two tribology parameters, so, the tribological change of the machined surface.
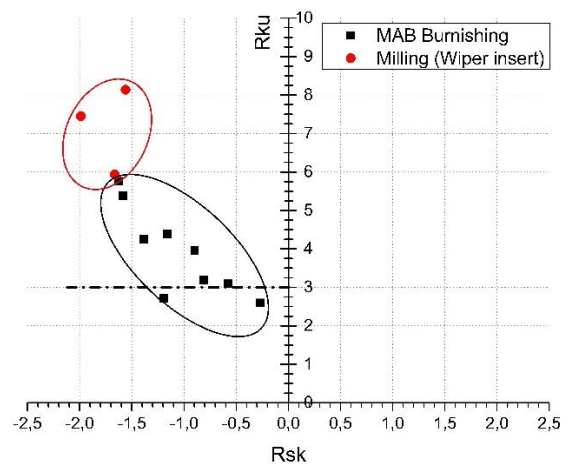

Fig. 20. Topological map of MABB technology

According to the Fig. 20. the number of 2 and 4 experiments are appropriate in tribological aspect and the 6 and 7 are near the $R_{ku}=3$ line so it is acceptable for subordinate places (e.g. conventional machine' sledge), too. It should be noted that the resulted surfaces of milling are also near the $R_{ku}=3$ line because the applied inserts had Wiper geometry. This geometry can produce better surface quality than a conventional insert with similar feed parameter, but it requires special, prescribed axial depth [38]. This positions of the burnished surfaces represent charactteristics with specially useful surfaces under extreme fine applications.

7. Conclusions

The aim of this paper is to analyze the optimum gap for Magnetic Assisted Ball Burnishing (MABB) and to determine the optimal machining parameters in order to prove that the introduced novel tool is a promising solution for MABB machining.

Calculation and experiments were used for analysing the rotating dynamometer. Both of methods gave the optimum gap, furthermore it was determined using the KISTLER rotating dynamometer that the burnishing force of 80N per ball is resulted.

As shown in Fig. 9. the influence of gap is significant because 1mm displacement of the tool means about 50-80N force reduction.

The authors formulated the following conclusions:

1. The optimal working gap to create low surface roughness are between 8,5 and 11,5 according to Fig. 13. and Table 4.

2. The optimal working gap to achieve the maximum burnishing force is h=10 mm.

3. To manufacture low R_a surface roughness the feed has the highest effect.

4. In tribological aspect the MABB processing under certain condition is able to produce fine surfaces.

5. Compared to the MABB process with grinding, the machined surface quality is an order better in tribological aspect (Fig. 19. and 20.)

Based on these results, it has been proved that the MABB tool is promising for roller burnishing flat or (thanks to the flexible balls fixing) near-to-flat (3D harmonic surfaces with flat extension) surfaces. The positions of the resulted burnished surfaces represent charactteristics being especially useful under extreme fine applications.

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