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The Effect of Magnetic Assisted Ball Burnishing on the Corrosion Resistance of C45 Steel

Zsolt Ferenc Kovács[1, 3] [0000-0002-6995-6508], Zsolt János Viharos[1, 2] [0000-0002-9561-6857] and János Kodácsy[1]

[1] John von Neumann University, GAMF Faculty of Engineering and Computer Science, Dep. of Vehicle and Faculty of Economics and Business, Dep. of Economics and Law, Kecskemét H-6000 Hungary
kovacs.zsolt@gamf.uni-neumann.hu, kodacsy.janos@gamf.uni-neumann.hu

[2] Institute for Computer Science and Control, Research Laboratory on Engineering and Management Intelligence, Intelligent Processes Research Group, Budapest H-1111 Hungary
viharos.zsolt@sztaki.hu

[3] Budapest University of Technology and Economics, Department of Manufacturing Science and Technology, Budapest H-1111 Hungary
kovacszs@manuf.bme.hu

Abstract. The development of modern science requires developing more economical, more environmentally friendly and more efficient procedures in the area of machine parts production as well. Corrosion, as a natural process, shortens the lifetime of our structures and machines. Although there are corrosion-resistant materials and various ways of protections against corrosion, all of them result in more expensive and more complex solutions. The increase in the corrosion resistance of metals can be achieved not only by applying surface protective coatings, but also by the usage of more economical and more efficient manufacturing processes. The developed, novel technology - Magnetic Assisted Ball Burnishing (MABB) - helps to increase the hardness of the surface and to reduce the surface roughness in the same time. This article investigates the effects of MABB machined workpieces against corrosion. The corrosion rate and the related technological parameters were optimized by the well-known Taguchi method. Corrosion tests were performed with a BioLogic SP-150 potentiostat in a conventional three-electrode corrosion cell. The recorded Tafel curves of the different specimens enable the calculation of the corrosion rate and time. The results prove that the corrosion resistance can be slightly increased by MABB machining, but it depends on the tool feed rate and the premachined surface roughness. The machining speed and the burnishing strategies show significant effects on the corrosion rate as well. The introduced MABB tool enables the reduction of the costs of further working-surface postprocessing, the increase in the hardness and lifetime of the treated surfaces, while surface roughness can be significantly reduced.

Keywords: Ball Burnishing, Edge Rounding, Magnetic Assisted Machining

1 Introduction

Numerous attempts and solutions have been made to slow down and prevent corrosion, which are able to protect the equipment exposed to corrosion. These methods are usually based on the application of coating or protective layers. However, up-to-date engineering is looking for those processes where, instead of the subsequent application of surface protection materials, the manufacturing technology itself can provide the solution for corrosion protection, such a result can be achieved by methods of causing surface plastic deformation.

In the paper, application of Magnetic Assisted Ball Burnishing (MABB) tool is examined, which machining is not yet widespread in production, and which, based on the data so far, provides an extremely promising method in corrosion protection as well beyond other positive effect on the machine workpiece.

According to the ISO 8044 standard, corrosion is a physico-chemical interaction between the metal and its environment, as a result of which the properties of the metal change and often the functional characteristics of the metal, the environment and the technical system consisting of them deteriorate [1].

According to the reaction procedure, the corrosion processes can be classified into the following two groups [2, 3]:

- chemical corrosion and
- electrochemical corrosion.

It is a generally accepted fact in the engineering sciences that surface roughness values are closely related to corrosion resistance [4 - 6].

With surface burnishing, during machining the tool presses down on the material surface, so that the surface layer start to flow and so the roughness peaks begin to fill-in the valleys, as shown in Fig. 1.

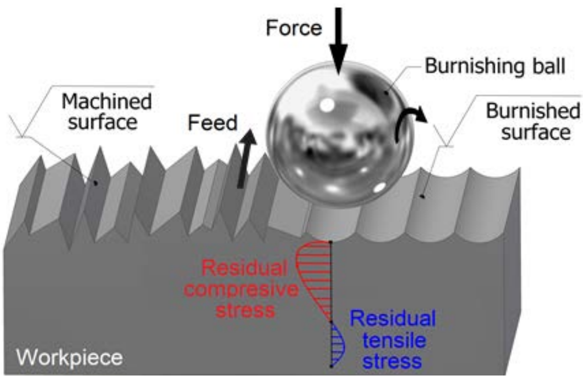

Fig. 1. Principles of ball burnishing process

As the surface layer deforms plastically, it causes hardness increases, too. The principle of magnetic assisted ball burnishing is that the tool travels along the surface of the workpiece at a given speed in a straight line or in another given path. The

MABB tool contains a neodymium permanent magnet, it can be clamped easily in a CNC milling machine, so that the finishing operation of the workpiece can be performed in the milling machine immediately after machining, which saves significant time and money. Its construction is simple (see in Fig. 2.) and it does not require any special maintenance.

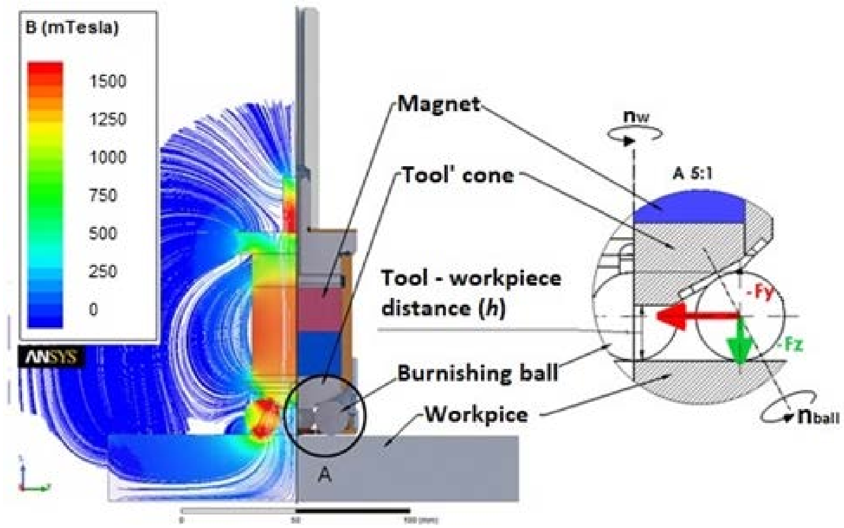

Fig. 2. Principles and parts of the MABB tool

Honess et al. (2006) published on surface quality and corrosion resistance of stainless steels. According to their results, if the average roughness is greater than 1 µm, the grooves and pits deepness of the surface can hold enough chloride ions, which leads to corrosion. If the average roughness on the surface can be reduced below 0.5 µm, the chance that the above-mentioned chloride ions are significantly reduced in the pits, so, this phenomenon is almost eliminated [4].

Asma et al (2011) investigated the relationship between surface roughness values and corrosion resistance capabilities on C22E steel in a carbon dioxide environment. During their experiment, the specimens were finished with silicon carbide abrasive papers of different particle sizes. It has been shown that specimens machined with increasingly finer abrasive papers showed improved corrosion resistance capabilities, however, the differences in corrosion are very small and are therefore not considered significant [5].

In Hryniewicz and Rokosz's (2004) analyzed the relationship between surface roughness and corrosion resistance for C45 type steel. The surface of the specimens was sanded and polished with different grain sized sandpapers. The prepared samples were tested in 3% and 0.03% sodium chlorides. The difference between the coarsest 180 sandpaper, and the finer 4000 sandpaper was nearly three times greater for the corrosion resistance in favor of the finer one, after the treatment with the 3% chlorides. Also, with 0.03% chloride, a significant, 1.6-fold improvement was achieved with the finer abrasive one[6].

The previously presented studies and experiments concerned surfaces handled by abrasive machining. Burnishing process significantly differs from these. A fundamental difference is that no chips are separated during rolling, so that the grain structure of the material is not damaged as during abrasive machining.

Salahshoor (2017) investigated the possibility of increasing the corrosion resistance of cylindrical MgCa0.8 alloy by ball burnishing. This study is so important because this alloy, which has very good properties among implants, corrodes very quickly in the human body, so the current usability of the material is economically unsatisfactory and also exposes the patient further surgery. In the test, the author made three flat milled and three burnished specimens with different rolling forces at different cutting speeds. The corrosion resistance of the specimens was compared by Hank's balanced salt solution test. Without wishing to be exhaustive, its results were as follows [7]:

- much less and more uniform corrosion products were produced on the rolled samples than on the machined samples,

- as the burnishing force increased, more and more corrosion occurred on the specimens.

Saldaña-Robles et al. (2018) studied the effect of rolling on surface roughness, surface hardness, and corrosion resistance. The material in each case was C45 cylindrical steel, the surfaces were pre-machined by turning. Corrosion resistances were compared on a turned and two rolled specimens, one of them had the lowest average surface roughness and the other one had the highest hardness. Based on their conclusions, the corrosion resistance of the rolled specimen was higher than at the turned one [8].

Hryniewicz and Rokosz (2005) conducted a similar experiment when investigated the effect of roller burnishing of C45 steel specimens on corrosion resistance. They compared the rolled pieces with the polished ones. Roller burnishing not only resulted a significantly improved surface roughness, but it significantly improved the corrosion resistance as well. The polished samples were paired with rolled samples, ensuring that the surface roughness are similar. By comparison, it can be stated that the corrosion resistance was much better on rolled surfaces than on the polished one [9].

Based on the analysis of the state-of-the-art publications, it can be stated that the conventional burnishing has significant effect on corrosion behaviour. However, there are scientific result only for cylindrical workpieces, so that, it is unknown, , that in the case of flat surfaces one may had a similar positive surface improvement. In the case, if it has positive effect, another important question arises: what extent can the MABB improve it? So, the main aim of this paper is to get the exact answer for these assumptions and challenges.

2 Description of the experimental work

The aim is not to create or develop a corrosion-resistant material, but to test the corrosion resistance of the machined workpieces with different burnishing strategies and machining conditions. The selected material was C45, since this is a general purpose, non-alloy material.

The dimensions of the specimens were: 200 mm long, 100 mm wide and 15 mm high. The experiments were performed on the basis of an experimental design by Taguchi [11] with different machining parameters and procedures (a total of 9 rolled plus 3 pre-machined samples). Each sample was pre-machined by milling or grinding. For face milling SECO APMX160408TR-M14 MP2500 inserts were used, while the grinding was performed on a surface grinder. The goal was to produce surfaces with different roughnesses.

After the preparatory processes, for the ball burnishing phase a CNC milling machine was suitable. An experimental design method (DoE) according to Taguchi was used to define the burnishing tests. The DoE table was designed by the MiniTab18 software, which consists of 3 levels and 4 factors. Table 1 shows the change in each factor, where the variables were:

A: Pre-machined roughness, *pre. Ra* (μm): ~0,8; ~1,6; ~2,4.
B: Feed, v_f (mm/min): 10 ; 30 ; 50.
C: Burnishing speed, v_b (m/min): 20 ; 50 ; 80.
D: Rate of burnishing, (%): 100 ; 150 ; 200.

The rate of rolling means the width of the tool path according to the width of the surface to be rolled by the tool (path diameter is approximately 47 mm). Thus, 100% means the straight-, 150% the small-, and 200% the large-cycloid path. The h distance between the workpiece and the tool was constants, its value was 10 mm [10].

Table 1. Design of Experiments (DoE) table for MABB corrosion test

Levels	Factors			
	A – *pre. Ra* (μm)	B - v_f (mm/min)	C - v_b (m/min)	D (%)
1	0,8	10	20	100
2	0,8	30	50	150
3	0,8	50	80	200
4	1,6	10	50	200
5	1,6	30	80	100
6	1,6	50	20	150
7	2,4	10	80	150
8	2,4	30	20	200
9	2,4	50	50	100

Traces of each rolling strategy are clearly visible on the burnished specimens, as shows the Fig. 3.

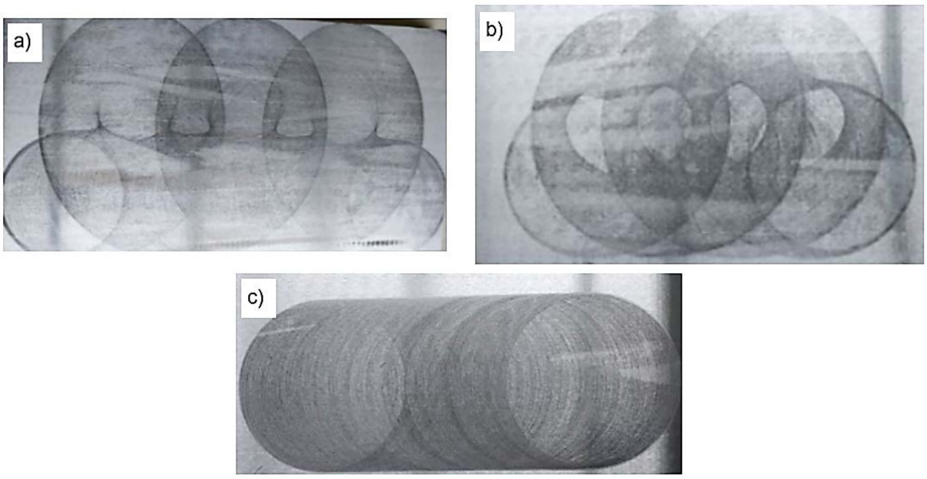

Fig. 3. Traces of burnishing strategies on the samples, a) Large-cycloid path (D-3=200%), b) Small-cycloid path (D-2=150%) and c) Straight path (D-1=100%)

3 Results of the burnished surface analysis

The corrosion tests on the machined surfaces were performed by a BioLogic SP-150 potentiostat and ECLab software, furthermore, a Zeiss EVO MA10 scanning electron microscope was also used to evaluated the corrosion behavior on the surface; during the related scanning the voltage was 20 kV. Roughness was measured on a MITUTOYO Formtracer SV-C3000 roughness tester.

3.1 Results of roughness analysis

The *Ra* average surface roughness was measured before and after ball burnishing. Based on the burnished *Ra* average roughness results, the bar graph shows *Ra* values in Fig. 4., whereat blue color marks the burnished surfaces having originally *Ra*=0.8 µm, green color marks the originally *Ra*=1.6 µm and yellow ones the originally *Ra*=2.4 µm surface roughness values. The Fig. 4. clearly represents that the *Ra* roughness values were significantly reduced compared to the original milled values.

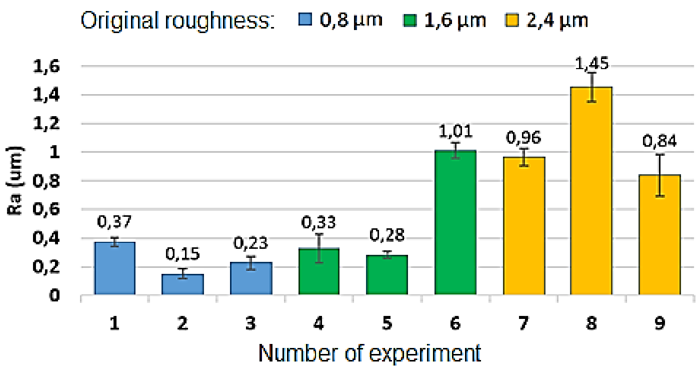

Fig. 4. Results of surface roughness measurement after ball burnishing

3.2 Results of corrosion analysis

The guidelines of the ASTM G102 standard for corrosion testing were used for evaluation. Corrosion values can be measured using the galvanic cell and polarization processes, including Tafel extrapolation or polarization resistance measurements. The first step is to convert the measured or estimated current to a special current density. This can be obtained as the quotient of the total current to the geometric surface size of the electrode dipped in the solution, with the assumption that the current is evenly distributed over the aforementioned area. In the case of galvanic pairs, the immersed surface of the anode should be used. The related calculation is (1):

$$i_{cor} = \frac{I_{cor}}{A} \tag{1}$$

where: i_{cor} is the corrosion current density (yA/cm^2), I_{cor} is the total anodic current (yA) and A is the corroded surface (cm^2).

Equivalent mass has to be calculated for clean cells (2):

$$EW = \frac{W}{n} \tag{2}$$

where: W is the atomic mass of the element and n is the number of electrons required to oxidize an atom in the corrosion process, which is the valence of the element.

Relationship to equivalent mass to be used for alloys (3):

$$Q = \sum \frac{ni \cdot fi}{Wi} \tag{3}$$

where: fi is the mass of the i-th element of the alloy, Wi is the atomic mass of the i-th element of the alloy and ni = valence of the i-th element of the alloy.

Thus, the equivalent mass is a reciprocal (4):

$$EW = \frac{1}{\sum \frac{ni \cdot fi}{Wi}} \tag{4}$$

Faraday's law can be used to calculate the corrosion rate CR (mm/year) by (5):

$$CR = K_1 \frac{i_{cor}}{\rho} EW \tag{5}$$

where: $K_1 = 3.27 \cdot 10^{-3}$ (mm·g/µA·cm·year) and ρ the density of materiel (g/cm^3).

Table 2. shows the calculated equilibrium mass, the calculated density, the corrosion current obtained from the evaluation, and Fig. 5. shows the measured exact surface area after corrosion from the stereomicroscopic images.

Table 2. Corrosion rate values after one hour - measurement.

Number of experiments	*Ew* (-)	*ρ* (g/cm^3)	I_{cor} (µA)	*A* (mm^2)	i_{cor} (µA/cm^2)	*CR* (mm/year)
1			6977,533	239,829	29,094	0,254
2			7270,618	207,698	35,006	0,267
3			7647,384	194,627	39,293	0,236
4			3914,594	194,164	20,161	0,246
5	19,293	7,462	6348,125	179,147	35,435	0,296
6			6731,190	196,744	34,213	0,332
7			4534,413	217,317	20,865	0,170
8			6986,236	235,616	29,651	0,300
9			5830,740	194,261	30,015	0,289

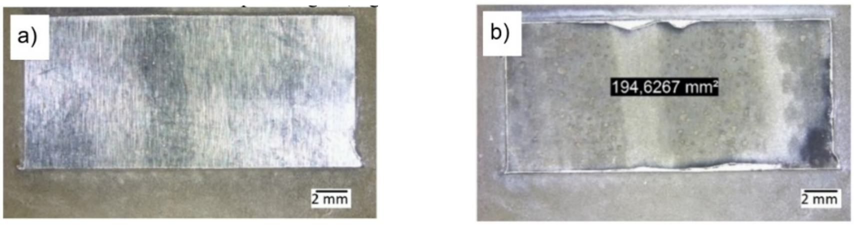

Fig. 5. Surface of sample 3 with stereomicroscope measurement, a) before corrosion and b) after corrosion

The corrosion current can be obtained from the Tafel curves (Fig. 6., according to the ASTM G102 standard).

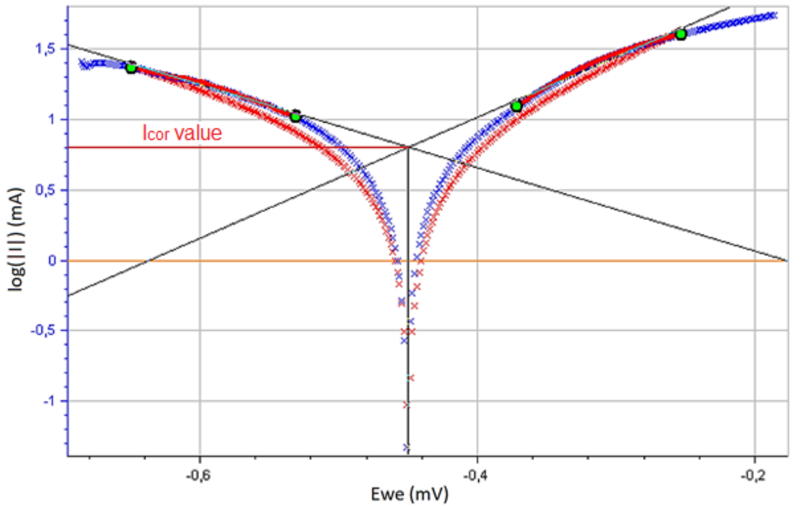

Fig. 6. Tafel curve of sample 5 after 1 hour of soaking

It was measured after a soaking time of 1 hour in electrolyte. The measurement was performed at a scanning speed of 90 mV/min, so one measurement takes 10 minutes and 33 seconds. A tangent shall be fitted to the straight part of the descending and rising stems of the curve and the point intersected by them shall give the corrosion current.

3.3 Roughness and corrosion common effects

Based on the tests performed, results can be obtained in which the corrosion rate values improve as a result of burnishing. The corrosion rates are shown in Fig. 7. (after a hour measurement).

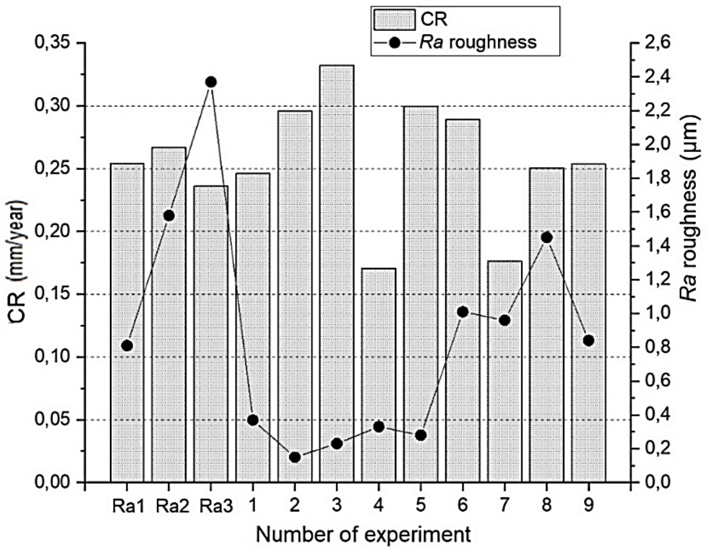

Fig. 7. Relationship between the corrosion rate and *Ra* surface roughness after MABB

According to Fig. 7, comparing the unburnished surfaces (Ra1, Ra2 and Ra3) to sample 1 (*pre. Ra*=0.8 µm; v_f =10 mm/min; v_b =20 m/min) when the rate of burnishing was 100%, the MABB had lower effect, while in the cases of sample 4 (*pre. Ra*=1.6 µm; v_f =10 mm/min; v_b =50 m/min; rate of burnishing 150%) and sample 7 (*pre. Ra*=2.4 µm; v_f =10 mm/min; v_b =80 m/min; rate of burnishing 150%) they succeed in a higher corrosion resistance. Furthermore, it can be seen that the sample 2 (*pre. Ra*=0.8 µm; v_f =30 mm/min; v_b =50 m/min; rate of burnishing 150%) and sample 3 (*pre. Ra*=0.8 µm; v_f =50 mm/min; v_b =50 m/min; rate of burnishing 200%) there were a significant deterioration in the corrosion resistance. What these samples have in common is that they were made by grinding. During grinding, higher amount of heat was given to the surface, tensile stress was generated from it, and possible grinding microcracks may have contributed to the experienced deterioration.

3.4 Technology set-up for the highest corrosion resistance

To obtain an accumulated result on the effects of each factors, the $(S/N)_S$ values have be calculated according to the Taguchi method [11] e.g. in Minitab 17 software. The "Smaller is better" analysis was chosen because the goal was to achieve the lowest possible corrosion resistance value. The effects of each factor on the corrosion rate are shown in Fig. 8.

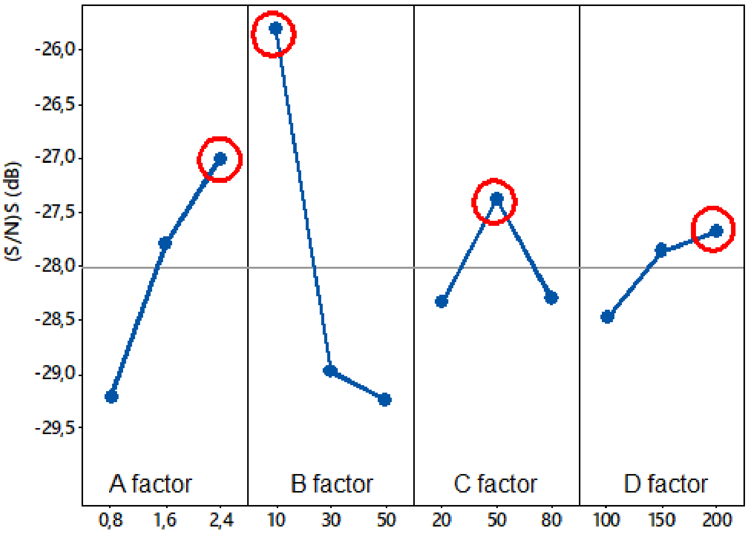

Fig. 8. Effect of burnishing factors on corrosion rate, A factor: Pre-machined roughness, B factor: Burnishing feed, C factor: Burnishing speed, D factor: Rate of burnishing: Rate of burnishing.

Based on Fig. 7. and 8., it can be identified that surfaces when higher MABB burnishing feed was applied (3; 6 and 9) show even higher corrosion rate compared to the pre-machined surfaces, while those which were machined by lower burnishing feed, resulted in lower corrosion rates. Thus, the lower the feed is, the better are the corrosion properties of the resulted workpiece. As shown in Fig. 8, *the pre-machined surface roughness has the most significant effect followed by the burnishing feed on the corrosion. All this means that the corrosion resistance of surfaces depends not only on the low ball burnished surface roughness, but also on the microgeometric structure of the surface, which is affected by the low feed.*

The highest level in the corrosion resistance can be achieved by (A3-B1-C2-D3), namely pre-machined roughness: 2.4 µm, feed rate of 10 mm/min, rolling speed of 50 m/min and with 200% high cyclic path.

4 Conclusions

Numerous attempts and solutions have been made to slow down and prevent corrosion, which are able to protect the equipment exposed to corrosion. In the paper, application of Magnetic Assisted Ball Burnishing (MABB) tool is examined, which machining is not yet widespread in production, and which, based on the data so far, provides an extremely promising method in corrosion protection as well beyond other positive effect on the machine workpiece.

The experimental results mirrored that there was less corrosion on the burnished surfaces and also the overall corrosion had much more even, and so, better distribution on the surface. Furthermore, looking at the less MABB burnished sample 1 and the highly MABB burnished sample 7, one might see that large parts of sample 7 stayed still resistant to corrosion, while uniform corrosion was observed over the entire surface of sample 1 (Fig. 9 and Fig. 10.).

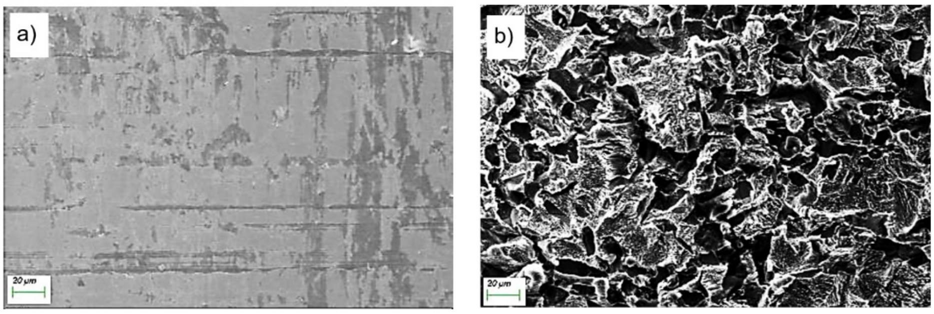

Fig. 9. SEM images of samples 1 (less MABB burnished) a) before and b) after corrosion test (N=1000×)

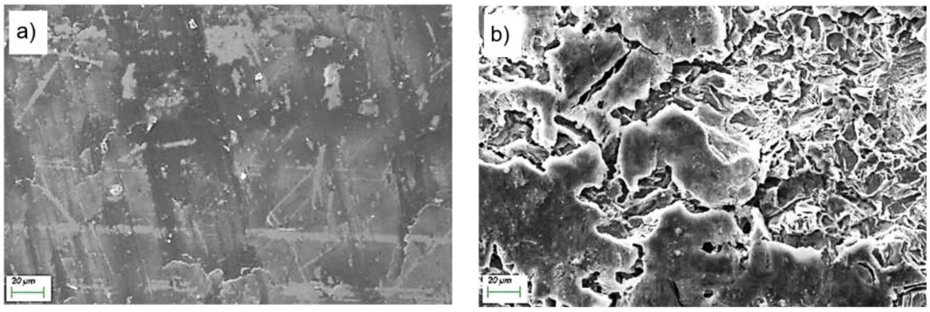

Fig. 10. SEM images of samples 7 (highly MABB burnished) a) before and b) after corrosion test (N=1000×)

The surface corrosion resistance of non-alloy structural steels (e.g. C45) can be improved by the introduced magnetic assisted ball burnishing:

- In terms of increasing the corrosion resistance, the burnishing feed has the greatest effect, so the lower burnishing feed can produce higher corrosion resistance surface and
- the studied cycloid burnishing strategy has also positive effect on corrosion resistance.

From these statements it can be concluded that the degree of burnishing (number of rolls) has an important effect on the corrosion resistance of the surface. Furthermore, as a result, thanks to the MABB burnishing, for example surfaces of workpiece parts can be exposed to moisture or to a corrosive medium for a short time because MABB prevents the starting of the corrosion.

Overall, MABB technology can, under certain conditions, be an effective tool in short term for corrosion protection of surfaces.

5 Nomenclature

A	corroded surface (cm^2)
CR	corrosion rate (mm/year)
fi	mass of the i-th element of the alloy
h	gap between the tool and workpiece (mm)
pre. Ra	pre-machined *Ra* roughness (µm)
i_{cor}	corrosion current density (yA/cm^2)
I_{cor}	total anodic current (yA)
n I	number of electrons required to oxidize an atom in the corrosion process
ni	valence of the i-th element of the alloy
v_b	burnishing speed ($m \cdot min^{-1}$)
v_f	burnishing feed ($mm \cdot min^{-1}$)
W	atomic mass of the element
Wi	atomic mass of the i-th element of the alloy
ρ	density of materiel (g/cm^3).

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