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## On the biological response of austenitic stainless steels after electrochemical -EP and MEP- polishing

Tadeusz Hryniewicz<sup>1,\*</sup>, Katarzyna Lewicka-Rataj<sup>2</sup>, Krzysztof Rokosz<sup>1</sup>

<sup>1</sup>Division of Bioengineering and Surface Electrochemistry, Department of Engineering and Informatics Systems, Faculty of Mechanical Engineering, Koszalin University of Technology, 15-17 Raclawicka Str., PL 75-620 Koszalin, Poland

<sup>2</sup>Division of Environmental Biology, Department of Waste Management, Faculty of Civil Engineering, Environment and Geodesy, Koszalin University of Technology, 2 Śniadeckich Str., PL 75-453 Koszalin, Poland

\*E-mail address: [Tadeusz.Hryniewicz@tu.koszalin.pl](mailto:Tadeusz.Hryniewicz@tu.koszalin.pl)

### ABSTRACT

The austenitic cold-rolled AISI 316L stainless steel was used for the studies. Corrosion resistance measurements were performed on the samples after three types of treatments: abrasive finishing (MP), standard electropolishing (EP), and magnetoelectropolishing (MEP). They were carried out in Ringer's solution at a room temperature, indicating a considerable difference in the breaking potential  $E_{\text{pit}}$  values, dependent on surface treatment. Two groups of samples, those after EP and MEP, were submerged in broth culture wild strain of *Escherichia coli* from contaminated river water. Images of the steel samples submerged for 2 and 4 hours are displayed in the paper. A statistical approach has been performed. In each case the number of bacteria deposited on the MEP steel samples was higher in comparison with that one noticed on EP samples, increasing much faster with time on the MEP ones.

**Keywords:** austenitic stainless steels, electrochemical polishing, electropolishing EP, magnetoelectropolishing MEP, water contamination, bacteria *Escherichia coli*, statistical approach

## 1. INTRODUCTION

Electropolishing (EP) is one of the most important surface finishing operations proposed to and performed on austenitic stainless steels [1-11]. Quite recently an enhanced oxidation-dissolution theory of electropolishing was developed [11]. To improve the surface finishing effects and modify the EP process, ultrasounds were sometimes introduced [1, 8]. On the other hand, the experiments with a magnetic field revealed a great potential in modifying and improving the surface finishing effects [10, 12-29]. Apart from diminishing surface roughness and highly improved gloss and brightness [1-3, 8-11], a great increase of corrosion resistance [8, 12-18] has been obtained. It was also proved, the medical and biological behavior of metallic surfaces after MEP processes are of great importance [10, 13-37]. Just recently also high-current density electropolishing (HDEP), with a current density of up to 2000 A/dm<sup>2</sup>, has been studied [38-42]. On one hand, progress in the inhibition of corrosion processes appears to be of a special attention e.g. in case of mild steels used for pipelines due to their inexpensiveness [43-47], and on the other, we have found an interesting behavior of stainless steels after electrochemical treatments. Our detailed study on stainless steels have shown that even if the surface film after the MEP process is only about 6-8 nm thick [48], and is thinner than that one usually obtained after EP and/or HDEP (about 10 nm), the corrosion resistance of MEP metal surfaces is higher and their biological behavior is more advantageous in practice than those ones after a standard electropolishing [1, 8-32, 36-42, 48].

The present study was to reveal the biological behavior of the stainless steel surfaces after EP and MEP, if being submerged in broth culture wild strain of *Escherichia coli* from contaminated river water. The results of the experiments are juxtaposed with surface layer characteristics, general corrosion behavior and a pitting corrosion potential of the surface treated 316L stainless steel.

## 2. METHOD

The austenitic cold-rolled AISI 316L stainless steel was used for the studies. The samples of dimensions 100 × 10 × 1 mm were cut off of the metal sheet: 3 samples were subjected to abrasive mechanical polishing (MP) using SiC paper of 1000 grit size, 3 of them were subjected to a standard electropolishing EP (on the plateau level [1, 8-11]), and 3 others were magnetoelectropolished MEP in a similar cell and current density conditions under a magnetic field, in the process as characterized elsewhere [9-22, 27, 32]. The corrosion studies were carried out both in 3 wt% NaCl solution, and in Ringer's solution at a room temperature, with pitting corrosion potential  $E_{pit}$  measurements performed accordingly and with the procedure described elsewhere [27].

After EP and MEP treatments, the samples were submerged in broth culture wild strain *Escherichia coli* coming straight from local Dzierżęcinka river (the specific *E. coli* bacteria were not identified for the study). Samples of stainless steel were removed from the liquid culture after 2 and 4 hours of incubation and gently washed in 0.85% NaCl solution to remove non-adhered cells. The bacteria adsorbed on the stainless steel surface after staining with DAPI (4',6-diamidino-2-phenylindole) fluorochrome were observed at the fluorescence microscope Nikon 80i equipped with camera Nikon DS-Ri1. The bacteria were counted from

the 20 fields of view in each of sample. The average amount of bacterial cells were converted per square millimeter/mm<sup>2</sup> surface of stainless steel sample.

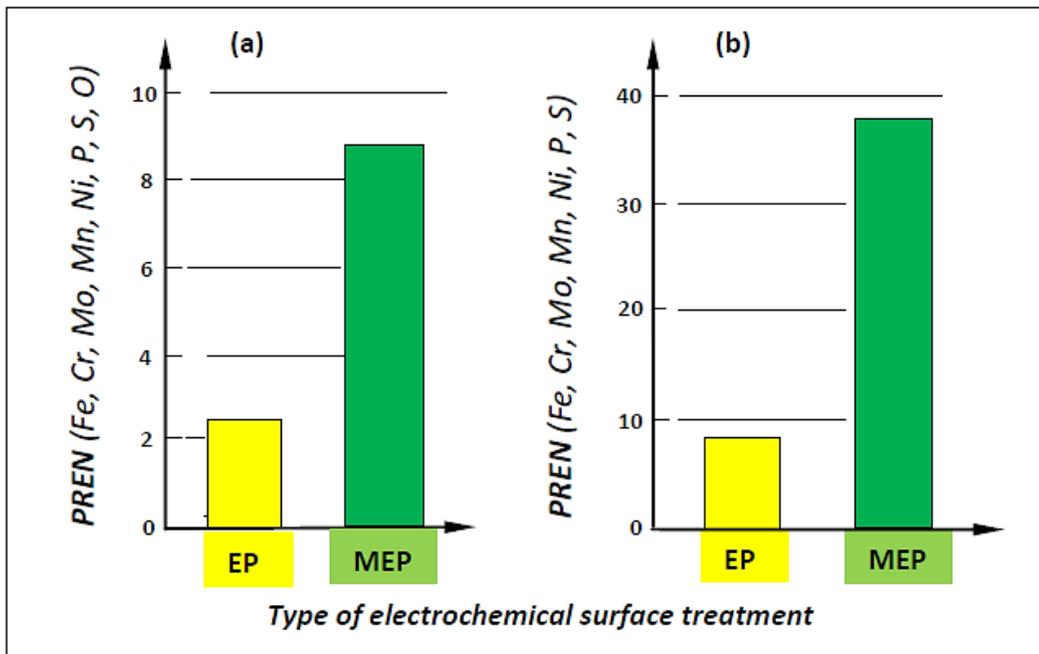
### 3. RESULTS

One of the essential characteristic features of stainless steels containing molybdenum is PREN (Pitting Resistance Equivalent Number) calculated from the following formula:

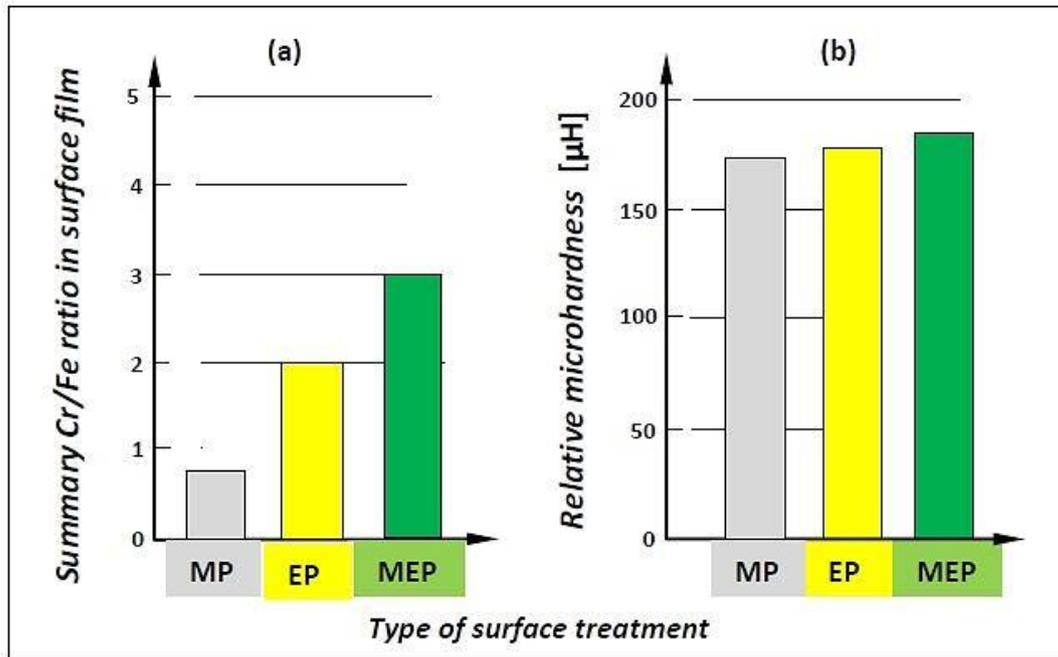
$$\text{PREN} = \text{Cr [at\%]} + 3.3 \text{ Mo [at\%]}$$

referred to the surface film composition: (a) including oxygen – PREN (Fe, Cr, Mo, Mn, Ni, P, S, O), and/or (b) without it – PREN (Fe, Cr, Mo, Mn, Ni, P, S). Results of PREN measurements performed on AISI 316L SS after a standard electropolishing EP, and magnetoelectropolishing MEP, are presented in Fig. 1. It appears, in both cases – including oxygen (Fig. 1a), and/or without it (Fig. 1b) – the value of PREN is much higher after MEP than that one after EP operation.

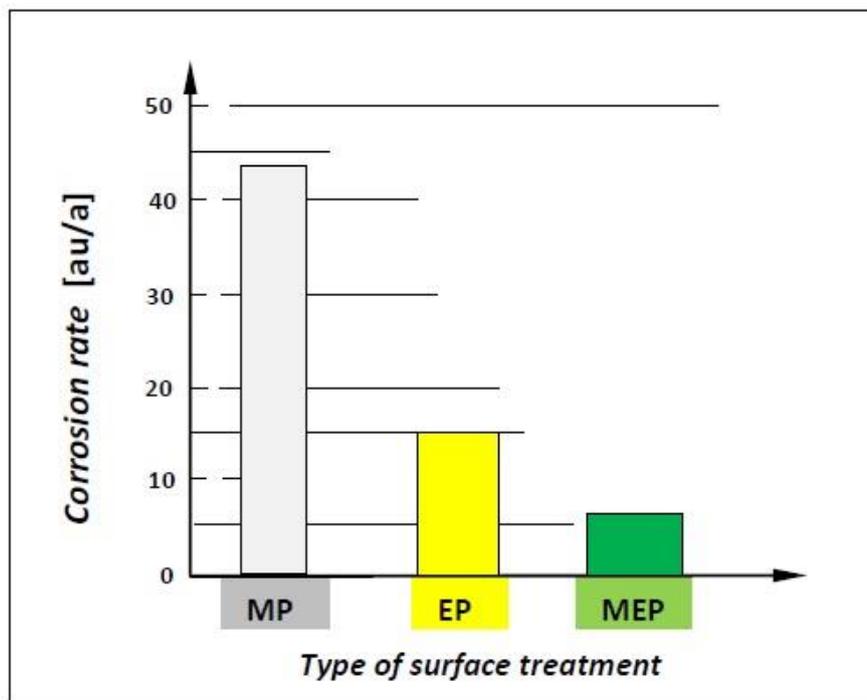
In Fig. 2, the comparison of summary results of Cr/Fe ratio of surface film (a), and the relative microhardness measurement results (b) on AISI 31L SS surface studied after consecutive treatments: MP – abrasive polishing EP – standard electropolishing, and MEP – magnetoelectropolishing, are presented. One may easily notice the increasing Cr/Fe ratio value measured after consecutive surface treatments, with the lowest – after MP (about 1.75), higher after EP (about 2), and the highest – after MEP, equaling about 3. On the other hand, microhardness measured after these three treatments, was increasing insignificantly, very slightly with consecutive sample, starting from MP, through EP, and MEP.



**Fig. 1.** Comparison of pitting resistance equivalent number (PREN) of AISI 316L SS calculated after: EP – standard electropolishing, and MEP – magnetoelectropolishing



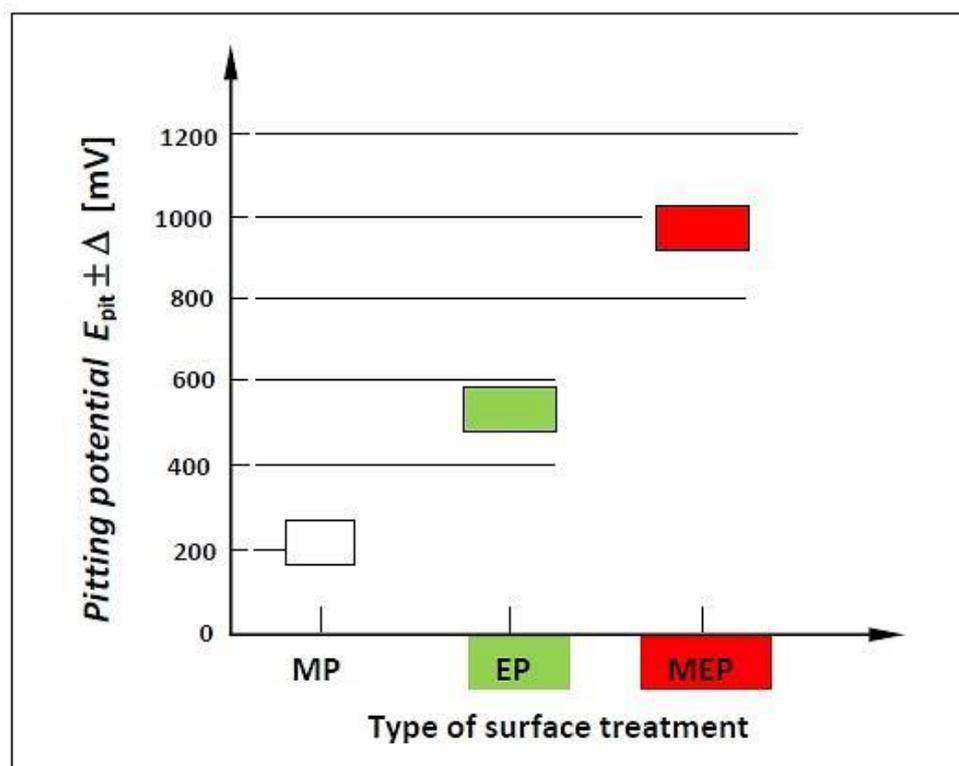
**Fig. 2.** Comparison of (a) summary results of Cr/Fe ratio of surface film, (b) relative microhardness measurements on AISI 31L SS surface studied after consecutive treatment: MP – abrasive polishing EP – standard electropolishing, and MEP – magnetoelectropolishing



**Fig. 3.** Comparison of corrosion rates of AISI 316L SS in 3 wt% aqueous NaCl solution after: MP – abrasive mechanical polishing (1000 grit size), EP – standard electropolishing, and MEP – magnetoelectropolishing (au/a – arbitrary unit per annum)

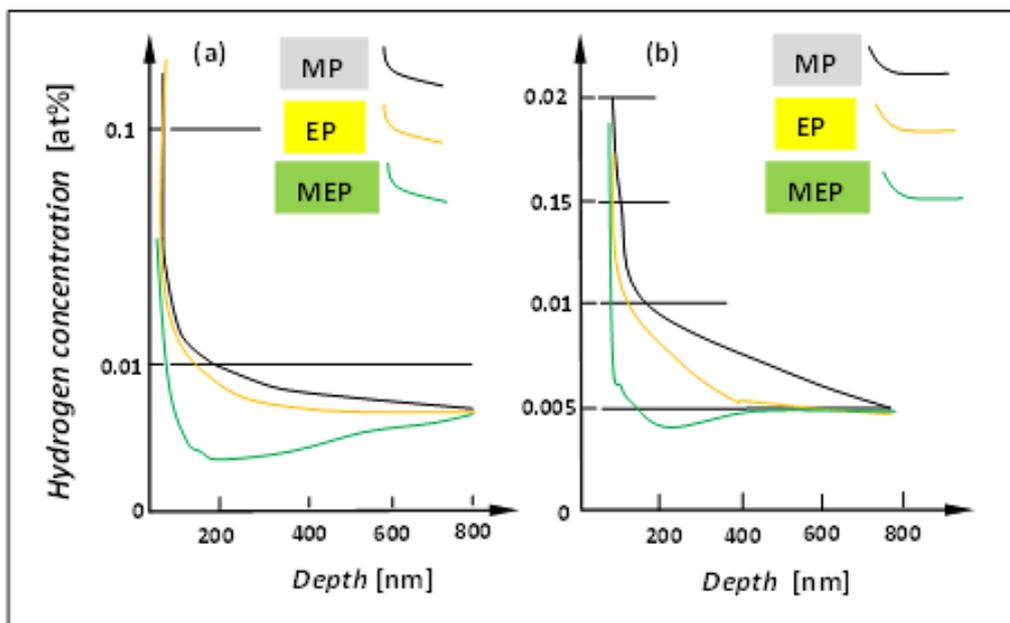
Our studies on corrosion rates (Fig. 3) measured in 3% NaCl solution (wt%) indicated a considerable decrease, starting from the highest corrosion rate – after MP, much lower – after EP, and the lowest – measured on the steel samples after MEP.

Pitting corrosion potentials  $E_{\text{pit}}$  [mV] of AISI 316L SS were studied after 3 surface treatment methods: (1) MP – abrasive mechanical polishing using SiC paper of 1000 grit size, (2) EP – standard electropolishing at a current density of about 100 A/dm<sup>2</sup>, and (3) MEP – magnetoelectropolishing at the same current density. Results displayed in Fig. 4 show increasing the breaking potential values  $E_{\text{pit}}$ , starting from the lowest – after MP, through much higher after EP, and the highest after magnetoelectropolishing MEP operation [29, 31, 36-37].



**Fig. 4.** Pitting corrosion potential  $E_{\text{pit}}$  [mV] of AISI 316L SS after: MP – abrasive mechanical polishing (1000 grit size), EP – standard electropolishing, and MEP – magnetoelectropolishing

Hydrogen contents in the surface layers of both CP Titanium Grade 2 [25], and stainless steel AISI 316L [24] were studied using Secondary Ion Mass Spectrometry (SIMS). Hydrogen concentration depth profiles of AISI 316L SS samples after MP – abrasive polishing, EP – standard electropolishing, and MEP – magnetoelectropolishing are shown in Fig. 5. In Fig. 5(a) there are results presented in logarithmic scale, and in Fig. 5(b) – in linear scale [24].



**Fig. 5.** Hydrogen concentration depth profiles of AISI 316L SS samples: results shown in logarithmic (a), and in linear scale (b)

One can easily notice in Fig. 5 that the hydrogenation of steel samples is slightly lower after standard electropolishing EP, then sharply decreasing and gaining the lowest value after magnetoelectropolishing MEP operation, in comparison with the hydrogen content in the samples after abrasive polishing MP.

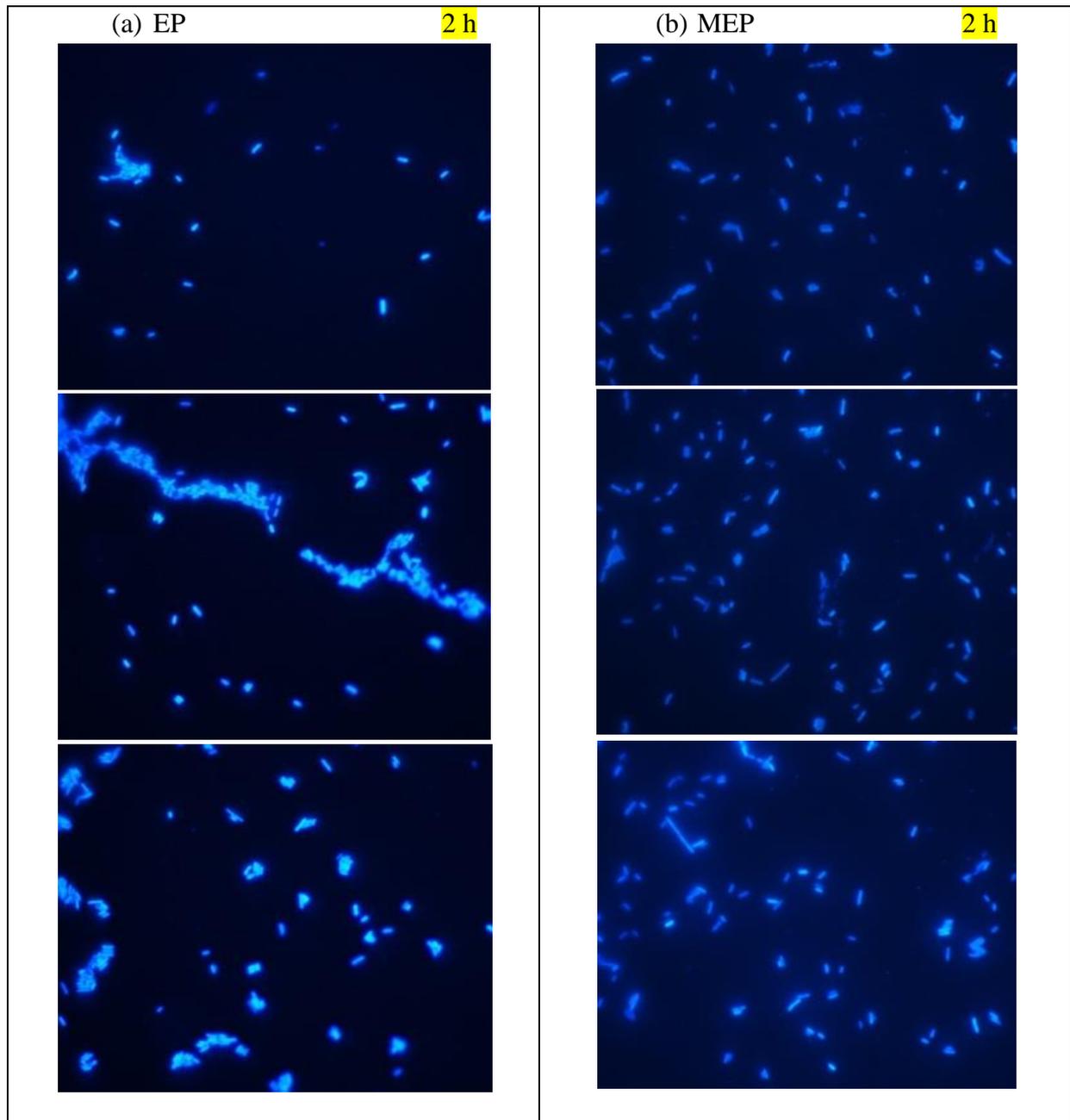
Results of the studies of steel samples after EP and MEP treatments, submerged in *Escherichia coli* liquid culture, are given in Figures 6 and 7. In Fig. 6, the pictures of bacteria deposited during 2 hours of immersion on each of the 3 EP and 3 MEP steel samples are presented.

In Fig. 7, the pictures of bacteria deposited during 4 hours of immersion on each of the 3 EP and 3 MEP steel samples are displayed. A considerable difference between the images of steel samples after electropolishing EP and magnetoelectropolishing MEP operations can be noticed, revealing much greater bacteria coverage observed on MEP steel samples.

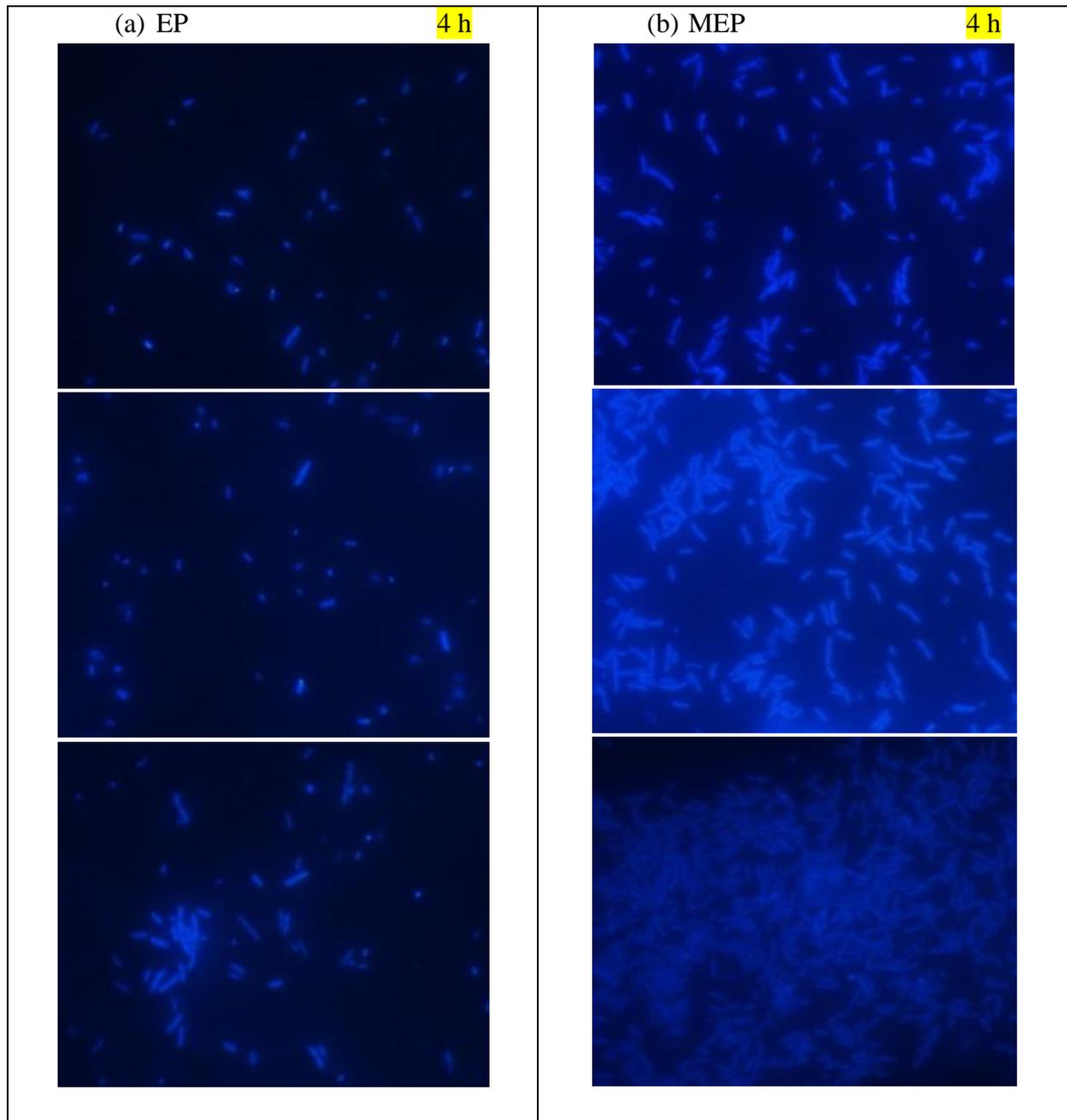
After calculating the number of *E. coli* bacteria deposited on each of EP and MEP samples, the statistical approach was done, concerning:

- (1) the first group of samples which were pulled out from the liquid culture *E. coli* after 2 hours, and
- (2) the second one – after 4 hours of resting in liquid culture *E. coli*.

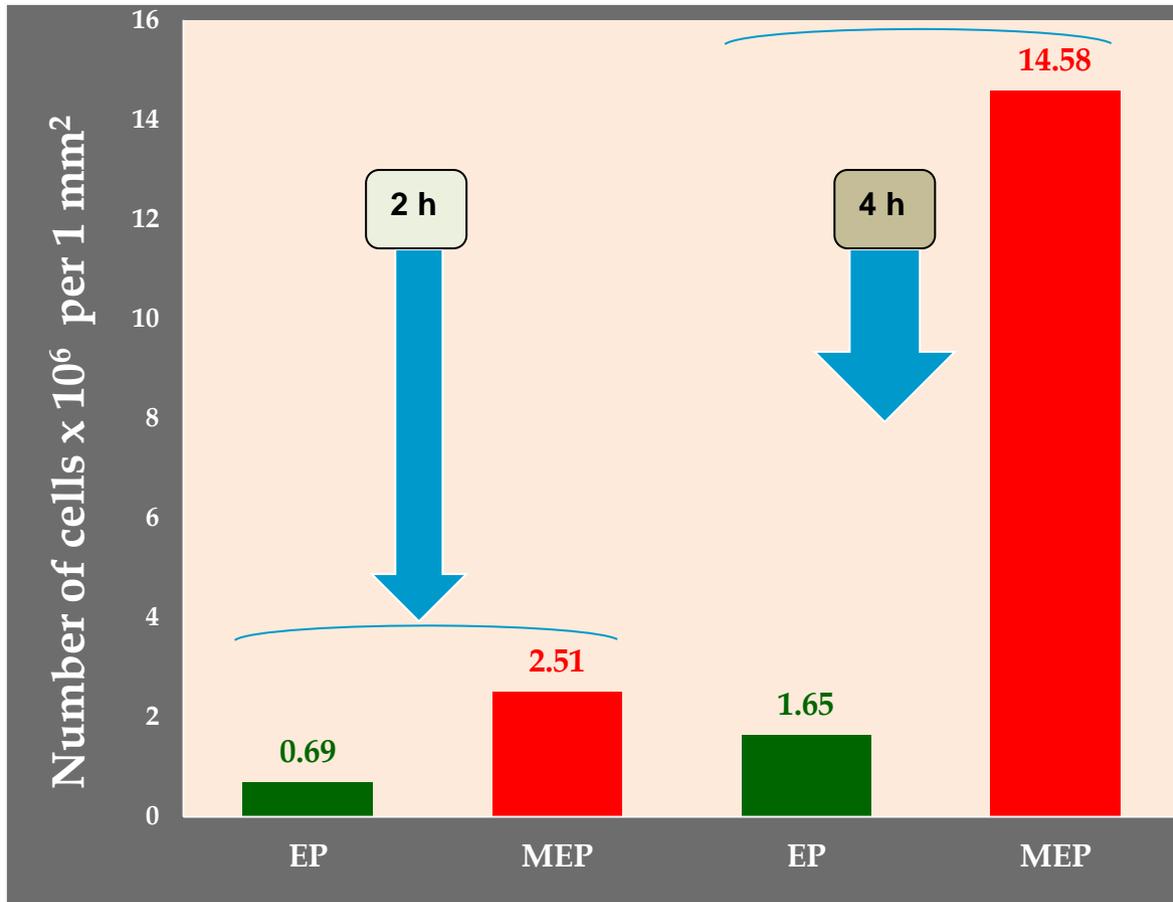
In each case the number of bacteria deposited on the MEP steel sample was higher in comparison with the number of bacteria found on EP sample, increasing in much greater degree with time on the magnetoelectropolished one (Fig. 8).



**Fig. 6.** Images of *Escherichia coli* bacteria deposited on AISI 316L SS surface after **2 hours** of submerging in the environment of liquid artificial medium: **(a)** 3 consecutive images of samples after EP, **(b)** 3 next images of the steel samples after MEP



**Fig. 7.** Images of *Escherichia coli* bacteria deposited on AISI 316L SS surface after **4 hours** of submerging in the environment of liquid artificial medium: **(a)** 3 consecutive images of samples after EP, **(b)** 3 next images of steel samples after MEP



**Fig. 8.** *Escherichia coli* bacteria deposition on AISI 316L surface after 2 h and 4 h of submerging in the environment of liquid artificial medium – number of cells on samples: **green** – after EP, **red** – after MEP

#### 4. CONCLUSIONS

The general studies carried out on AISI 316L stainless steel after abrasive polishing MP, and electrochemical polishing, EP and MEP, allowed to formulate some important conclusions:

- summary results of Cr/Fe ratio of 316L SS surface layer show an increase, starting from the lowest – after MP, higher – after EP, and the highest – after MEP
- corrosion rate, as measured in au/a, was the highest – after MP, lower – after EP, and the lowest – after MEP
- pitting corrosion potential  $E_{pit}$  grows with consecutive surface finishing operations, starting with the lowest – after MP, higher after EP, and the highest after MEP; this confirms our findings [31]
- hydrogen concentration in 316L SS surface layer was the highest in the samples after abrasive polishing MP, slightly lower after a standard electropolishing EP, and much decreased after magnetoelectropolishing MEP operation.

The introductory biological studies carried out on AISI 316L stainless steel after electrochemical polishing, EP and MEP, allowed to formulate the following conclusions:

- stainless steel, represented here by AISI 316L, after its surface electropolishing treatment behaves differently in the artificial medium contaminated by bacteria of *Escherichia coli* and containing nutrients for these, dependent on the sample surface treatment conditions
- after magnetoelectropolishing MEP process the steel surface attracts much more for *E. coli* bacteria to attach than the steel surface after a standard electropolishing EP
- the number of bacteria accumulated on a unit sample surface after MEP increases progressively with time at a much higher degree than that on the surface after EP.

An additional conclusion resulting from the studies is that such a steel surface after MEP may serve as the *Escherichia coli* bacteria separator.

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