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EROSION OF METALS BY PULSATING WATER JET

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Original scientific paper

The aim of the paper was to determine erosion effects of pulsating water jet impinging the surface of metal sample. The influence of repeated impacts of water pulses and impact velocity (operating pressure) on the erosion of metal surface was investigated. The development of erosion pattern with respect to number of impacts was analysed and discussed. It was found that erosion caused by repeated impacts of water pulses occurs in three stages. The stage of erosion of the surface can be determined by the behaviour of surface characteristics (such as *Ra* and *Rz*) with respect to number of impacts of pulsating water jet.

Keywords: *erosion effects, pulsating water jet, repeated impact, surface characteristics*

Erozija metala pomoću pulsirajućeg vodenog mlaza

Izvorni znanstveni članak

Cilj rada bio je utvrditi eroziju uzrokovanu pulsirajućim vodenim mlazom koji udara o površinu metalnog uzorka. Istražen je utjecaj ponovljenih djelovanja vodenih impulsa i utjecaja brzine (radnog tlaka) na eroziju metalne površine. Analiziran je i raspravljen razvoj erozijskog modela u odnosu na broj djelovanja. Utvrđeno je da se erozija uzrokovana opetovanim djelovanjem vodenih impulsa javlja u tri faze. Faza erozije površine može se odrediti pomoću ponašanja karakteristika površine (kao što su *Ra* i *Rz*) s obzirom na broj djelovanja pulsirajućeg vodenog mlaza.

Ključne riječi: *efekti erozije, ponovljeno djelovanje, pulsirajući vodeni mlaz, svojstva površine*

1 Introduction

It is well known that destructive effects of high-speed water jets can be enhanced by generation of pulsating water jets (see e.g. [1]). The pulsating water jets are generated by sufficiently high pressure pulsations in pressure water upstream the nozzle exit. Pressure pulsations change into velocity pulsations in the nozzle and the jet emerges from the nozzle exit as a continuous one with variable axial velocity. Owing to the variable velocity, the jet forms into pulses at certain standoff distance from the nozzle exit (at so called forced break-up length of the jet) and starts acting as a pulsating jet. Exploitation of effects associated with water pulses impingement on solids in a high-speed water jet cutting technology should lead to considerable improvement of its performance, better adaptation to more and more demanding environmental requirements, and consequently to more beneficial use of the technology also from the economical point of view.

The collision of a high-velocity liquid mass with a solid generates short high-pressure transients which can cause serious damage to the surface and interior of the target material. When studying the problem of the pressure developed by a liquid impact on a solid surface, it is necessary to take into account the fact that the liquid impact consists of two main stages. During the first stage, the liquid behaves in a compressible manner generating the so-called "water-hammer" pressures. These high pressures are responsible for most of the damage resulting from liquid impact on the solid surface. After the release of the impact pressure, the second stage of the liquid impact begins. It is characterised by the liquid flowing away from the point of impact. The velocity of this tangential flow may be as much as five times the impact velocity. Therefore, there are additional shear forces associated with the high speed flow across the surface acting on the surface in addition to the normal forces.

Study of material removal in water jet impingement processes in various materials leads to the identification of four primary modes by which water drop impingement can produce damage in materials: direct deformation, stress wave propagation, lateral outflow jetting and hydraulic penetration. The damage produced by one or more of these loading conditions on a material surface exposed to a single or multiple water drop impact is responsible for initiating damage and subsequent material removal.

An understanding of the effects associated with liquid impact erosion or water droplet impingement on solids is needed in a number of technological situations. The erosion of steam turbine blades and rain erosion of aircraft and missiles represent some of negative effects of liquid impact. In these cases, it is essential to know the mechanism of degradation of materials and identify a suitable material or coating to combat jet impingement erosion. The characteristics of damage to materials and parameters related to water droplet impingement have been extensively reviewed, and a number of fundamental studies on liquid impact or water droplets have been reported (see e.g. [2÷7]).

On the other hand, the effects can be utilized advantageously in many applications, such as surface treatment techniques to affect properties of surface layers e.g. by residual stress removal or peening [8÷11] or water jet spot welding [12].

The aim of presented study was to determine erosion effects of pulsating water jet impinging the surface of metal sample. The influence of repeated impacts of water pulses and impact velocity (operating pressure) on the erosion of metal surface was investigated. The development of erosion pattern was analysed and discussed in the paper.

2 Experimental facility

The experimental facility used for investigation of erosion effects of pulsating water jet impinging the surface of metallic samples consisted essentially of a high-pressure water supply system, a pulsating water jet generator, X-Y table for traversing of the jet over testing samples and devices for evaluation of the surface erosion of samples.

High-pressure water was supplied to the generator of pulsating water jet by a plunger pump capable to deliver up to 45 l/min of water at operating pressure up to 120 MPa. The generator was equipped with commercially available nozzle StoneAge Attack with orifice diameter of 1,60 mm. Operating pressure was measured at the inlet of pulsating jet generator by a piezoresistive pressure sensor Kristal RAG25A1000BC1H.

The pulsating water jet generator is based on the generation of acoustic waves by the action of the acoustic transducer on the pressure liquid and their transmission via pressure system to the nozzle. The high-pressure system with integrated acoustic generator of pressure pulsations consists of a cylindrical acoustic chamber connected to the liquid waveguide. The liquid waveguide is fitted with pressure liquid supply and equipped with the nozzle at the end. The acoustic actuator consisting of piezoelectric transducer and cylindrical waveguide is placed in the acoustic chamber (see Fig. 1). Pressure pulsations generated by acoustic actuator in acoustic chamber filled with pressure liquid are amplified by mechanical amplifier of pulsations and transferred by liquid waveguide to the nozzle. Liquid compressibility and tuning of the acoustic system are utilized for effective transfer of pulsating energy from the generator to the nozzle and/or nozzle system where pressure pulsations are transformed into velocity pulsations [13].

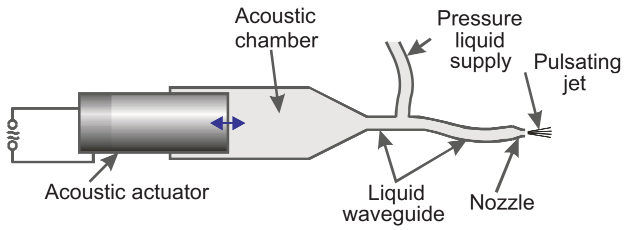

Figure 1 Schematic drawing of the high-pressure system with integrated acoustic generator of pressure pulsations

Generator of pulsating water jet used in the experiments was designed for maximum operating pressure of 100 MPa. The generator was equipped with piezoelectric transducer vibrating at the operating frequency of about 20 kHz and driven by ultrasonic generator Ecoson WO-UG_630-20 with maximum output power of 800 W. The generator enabled precise setting of operating time from 1 ms with precision of 1 ms. The feature was used for control of number of pulses impacting the surface of the testing sample.

Samples eroded by pulsating water jet were examined by optical profilometer MicroProf FRT to determine surface characteristics of eroded surfaces; appearance of the eroded spots was studied using confocal microscope Olympus OLS 3000 and optical microscope NIKON Eclipse 80i.

Test samples were prepared from stainless steel ČSN EN 17 347 (AISI 316Ti, DIN 1.4571). Basic properties of the steel are given in Tab. 1. Abrasive water jet technology was used to cut the samples from 10 mm thick sheet to eliminate thermal effects on the sample properties. Shape and dimensions of testing samples are shown in Figure 2. Magnetic grinder was used to grind top surface of samples. Subsequently, metallographic grinder Struers Tegra Pol 35 and sandpaper with grain sizes 320, 800, 1000, and 1200 was used to polish top surface of samples. The pressure forces of 10 N and rotation speed of 200 1/min were used for this operation. Finally, the top surface of the sample was polished by polishing diamond suspense with the grain size of 3 μm and 1 μm to brilliant polish.

Table 1 Basic properties of austenitic stainless steel ČSN EN 17 347

Chemical composition /wt. %					
C max.	Cr	Ni	Mo	Ti	Mn
0,12	17,5	10,5	2,0	0,5	2,0
Mechanical properties					
Yield strength $R_{p0,2}$ /MPa	Tensile strength R_m /MPa	Elongation δ_5 / %	Hardness Rockwell B /HR B	Hardness Brinell /HB	
>220	500-700	>45	95	217	

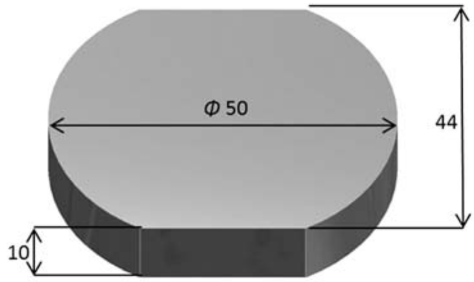

Figure 2 Shape and dimensions of testing sample

3 Experimental procedure

To expose the surface of the sample to required number of impacts of water pulses from pulsating water jet, the following testing procedure was developed. After setting of required standoff distance, the pump was turned on, proper operating pressure was adjusted and the pump was turned off. Then the pulsating water jet generator was moved over the sample to the required position and the pump was turned on. After 10 seconds delay on the spot, the pump was turned off. During the 10 seconds delay, ultrasonic generator was turned on for the given period of time to expose the sample to the required number of impacts of pulsating water jets. Preliminary tests proved that the exposure of the sample surface to the action of continuous jet for 10 seconds did not produce any detectable erosion of the sample under testing conditions used in the experiment.

Tests were performed at operating pressures of 10, 20, and 30 MPa (corresponding jet velocities were approx. 130, 180 and 220 m/s). Standoff distance was set to 40 mm for tests at operating pressure of 10 MPa and to 50 mm for tests at pressures of 20 and 30 MPa. These standoff distances were determined as optimal for given experimental conditions in previous tests. Pressure pulsations in pulsating water jet generator were generated at frequency of 21,25 kHz (readout from the display of ultrasonic generator); amplitude of vibration of ultrasonic sonotrode was set to 7 μm.

Nine areas of each sample were exposed to the action of pulsating jet according to predefined pattern. Duration of the action of pulsating water jet on the surface was changed from 0,05 s to 5 s. This provided a wide range of numbers of impacts of water pulses on the sample surface starting from 1.060 to 106.000 impacts. Additionally, one area of each sample was exposed to the action of continuous jet of the same parameters for 10 seconds to be able to compare continuous and pulsating jet effects on the surface.

Areas 5×5 mm exposed to the action of pulsating water jet impacts were scanned by optical profilometer MicroProf FRT with resolution of 5 μm. Then, two fields 2×2 mm were

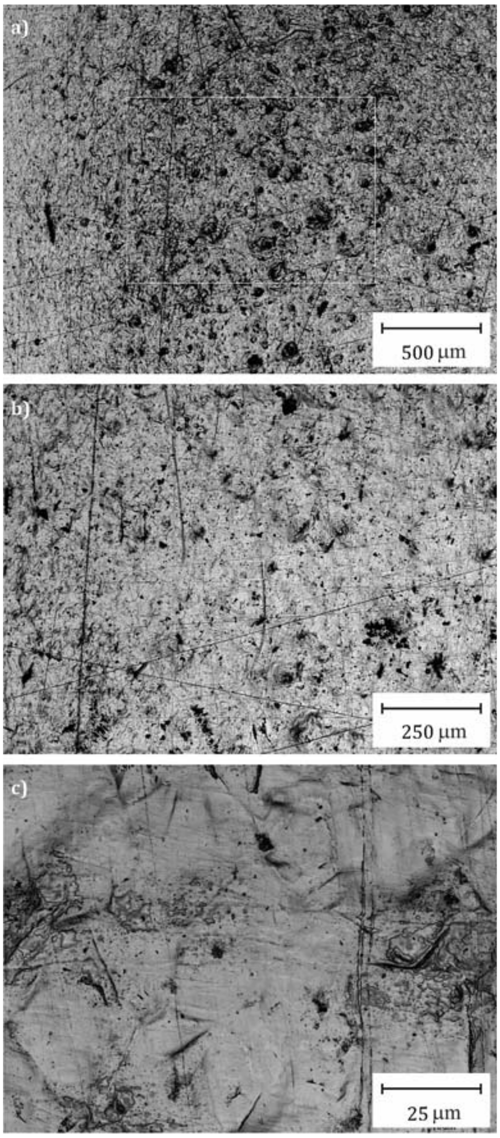

Figure 3 Real surface image of eroded stainless steel sample after 2.125 impacts of pulsating water jet showing the appearance of the eroded spot at different magnifications. Operating pressure 30 MPa, nozzle diameter 1,60 mm, standoff distance 50 mm.

selected in the obtained topography, the area was analysed after averaging and 3D surface parameters average roughness *Ra* and average maximum height of the profile *Rz* were determined.

Confocal microscope was used to obtain 3D real surface colour images. The size of the view area was 2,56 × 2,56 mm at objective lens magnification 5×. The areas exposed to the action of pulsating water jet impacts were scanned using lens magnification 5×, 10×, 20×, 50× and 100× and subsequently analysed.

The optical microscope NIKON Eclipse 80i equipped with the motorized scanning stage MÄRZHÄUSER SCAN-24-410 and the colour CCD camera NIKON DS-5M connected to PC was used to acquire the microscopic images. Every image was reconstructed automatically by "stitching" of 4 × 4 microscopic image fields using the image processing and analysis system NIS Elements v. 2.3 (Laboratory Imaging, Ltd.) The images were taken in reflected light (dark field technique) of the microscope. Large composed microscopic images of erosion patterns were obtained in this way and subsequently analysed.

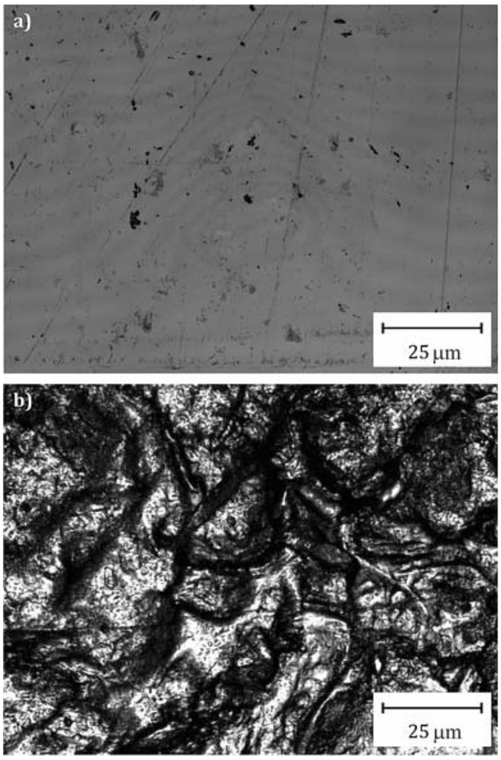

Figure 4 Real surface images of eroded stainless steel sample after 10 625 (a) and 106 250 (b) impacts of pulsating water jet. Operating pressure 30 MPa, nozzle diameter 1,60 mm, standoff distance 50 mm.

4 Results and discussion

4.1 Erosion of stainless steel

As can be seen in Fig. 3, erosion of tested stainless steel starts with roughening of the surface indicated by appearance of small surface depressions; some of them grow rapidly in size due to further impacts and new ones appear. There was observed also additional effect of the deformation – tilting the grains resulting in visibility of grain boundaries (see Fig. 3c). Some eroded spots also exhibit regions of plastic deformation, as can be seen in Fig. 4a.

When the number of impacts of pulsating water jet increases, the surface roughened by depressions and grain boundaries is further eroded (by action of both impact pressure and the shearing action of the outward flow) and surface pits appear. These pits subsequently spread and merge with further impacts to form an erosion crater in the specimen. This stage of erosion can be characterized by significant material loss. Subsequent repeated impacts of pulsating water jet deepen the erosion crater. Figure 4b illustrates appearance of the bottom of erosion crater. Development of the erosion on the surface of stainless steel sample by repeated impacts of pulsating water jet from surface depressions to erosion crater can be seen in Fig. 5.

It can be summarized (in accordance with findings published in [14]) that three stages of erosion can be observed in erosion of tested stainless steel by repeated impact of pulses of pulsating water jet. First stage (also called as initial incubation period) can be characterized by plastic or brittle deformation in the impacted surface; there is no erosion in sense of material loss during the first stage. During the second stage pits formed in the surface by removal of material begin to grow and cover the impact area. Erosion rate rises to a maximum at the second stage.

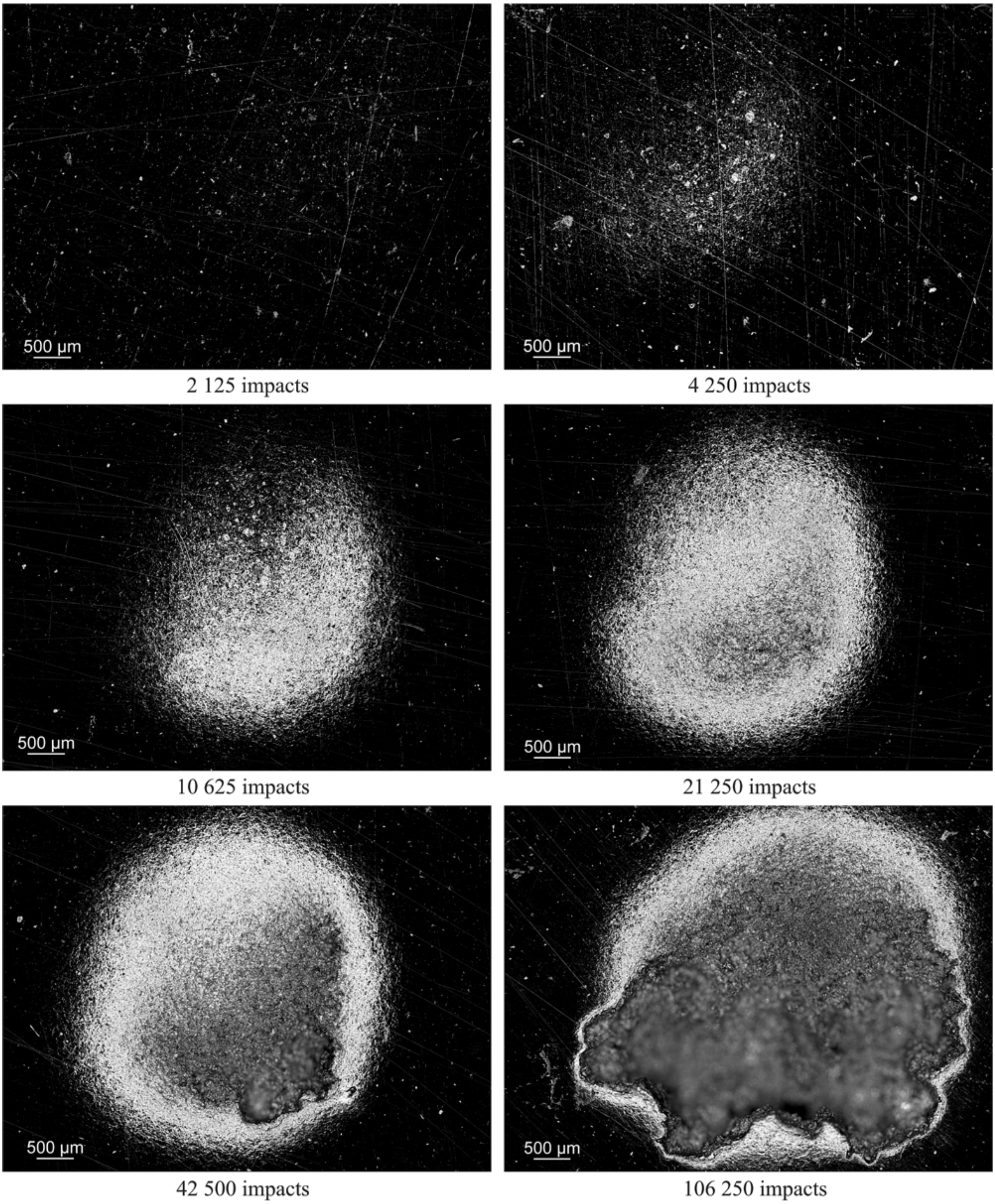

Figure 5 Micrographs of erosion development on stainless steel surface after given number of impacts of pulsating water jet. Operating pressure 30 MPa, nozzle diameter 1,60 mm, standoff distance 50 mm.

The third stage of erosion occurs after the merging of pits to form erosion crater; erosion rate decreases during the final stage of erosion because eroded area remains roughly constant and only the depth of erosion crater increases.

4.2 Surface characteristics

As mentioned above, surface characteristics of the surface exposed to various number of impacts of pulsating water jet were evaluated in terms of 3D surface parameters average roughness *Ra* and average maximum height of the profile *Rz*.

Obtained results indicate that the behaviour of surface characteristics *Ra* and *Rz* with respect to the number of impacts of pulsating water jet determines the stage of erosion of the surface, discussed in the previous section. The initial incubation period features low values of both *Ra* (in the range of tenth of m) and *Rz* (in the range of units of m). The second erosion stage can be characterized by step increase of values of *Ra* (up to about 10 m) and *Rz* (up to about 90 m) as a result of the growth of erosion pits over the impact area. At the third erosion stage, the rate of increase of *Ra* and *Rz* values decreases which corresponds to the deepening of erosion craters created in the impacted area. The above described behaviour is illustrated in Figs. 6 to 8.

At the operating pressure of 10 MPa, even 106 250 impacts of pulsating jet on the stainless steel surface do not produce any significant erosion. This corresponds to the relatively flat curves in Fig. 6 with almost constant values of *Ra* and *Rz* with respect to the number of impacts. Similar behaviour can be observed for operating pressure of 20 MPa in Fig. 7.

However, three regions of erosion can be distinguished in the graph presented in Fig. 8 for operating pressure of 30 MPa. The first region (up to approx. 20.000 impacts) exhibits almost constant values of *Ra* and *Rz*. This corresponds to the first stage of erosion (see above). The region from 20.000 to 40.000 impacts is characterized by rapid increase of values of both *Ra* and *Rz*. This corresponds to the second stage of erosion as discussed above. The third region (above 40.000 impacts), corresponding to the third stage of erosion, can be characterised by moderate increase of values of *Ra* and *Rz*.

5 Conclusion

Experimental work oriented at the determination of erosion effects of pulsating water jet impinging the surface of stainless steel sample proves that the erosion caused by repeated impacts of water pulses occurs in three stages. The initial stage of erosion exhibits plastic or brittle deformation in the impacted surface only. The second stage can be characterized by creation of erosion pits and their merging to form erosion crater whose depth increases at the third stage of erosion.

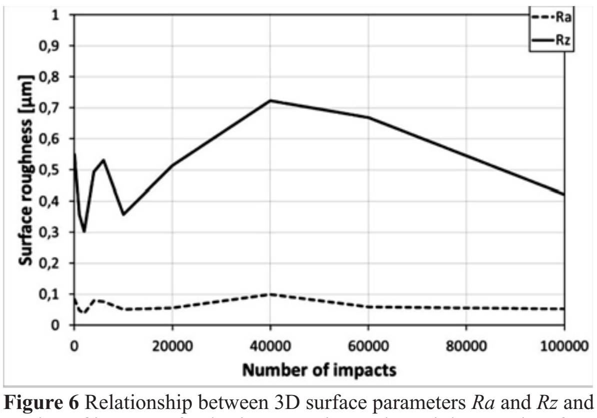

Figure 6 Relationship between 3D surface parameters *Ra* and *Rz* and number of impacts of pulsating water jet on the stainless steel surface. Operating pressure 10 MPa, nozzle diameter 1,60 m, standoff distance 40 m.

It was found that the second stage of erosion did not begin even after 106.250 impacts of pulsating water jet generated at pressures of 10 and 20 MPa. On the other hand, impacts of pulsating water jet generated at pressure of 30 MPa produced all three stages of erosion within the range of number of impacts from 1.062 to 106.000.

It was also found that the behaviour of surface characteristics (such as *Ra* and *Rz*) with respect to number of impacts of pulsating water jet determines the stage of erosion of the surface.

Next steps of the research in this area should be oriented at the study of the influence of nozzle diameter on the erosion by repeated impact of pulsating jet, investigation of changes in properties of surface layers due to impacts of water pulses using e.g. measurement of microhardness, and study of propagation of microcracks and fractures in the material caused by impacts (using X-ray tomography).

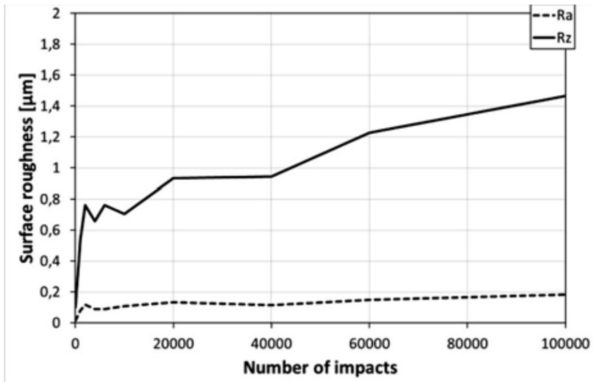

Figure 7 Relationship between 3D surface parameters *Ra* and *Rz* and number of impacts of pulsating water jet on the stainless steel surface. Operating pressure 20 MPa, nozzle diameter 1,60 m, standoff distance 50 m.

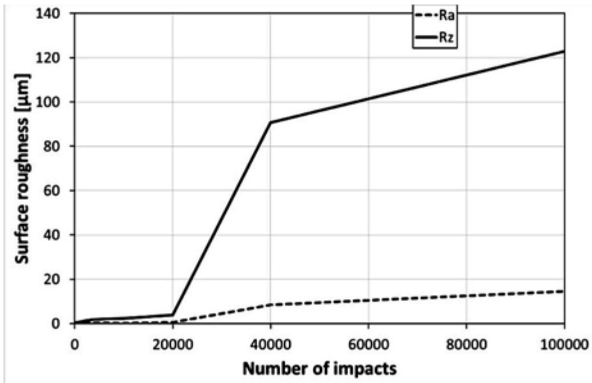

Figure 8 Relationship between 3D surface parameters *Ra* and *Rz* and number of impacts of pulsating water jet on the stainless steel surface. Operating pressure 30 MPa, nozzle diameter 1,60 m standoff distance 50 m.

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