Effect of Frequency Change During Pulsed Waterjet Interaction with Stainless Steel

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Abstract. In the present work a detailed effect of pulsating water jet treatment with the variation of standoff distance on the flat austenitic stainless steel surface has been studied. During the experimentation, at a traverse speed of 30 mm/s accidently the change in frequency was encountered in the repeated test (under same treatment condition) which has been reported in this work. The frequency was changed from $f = 20.11$ kHz to $f = 20.27$ kHz during the treatment process at the pressure of $p = 70$ MPa with variation in standoff distance was increased from $z = 5$ mm up to $z = 101$ mm (with step distance of 2 mm between successive standoff distance). The change in microstructural topography of the treated surface under the above-mentioned conditions was observed using scanning electron microscopy (SEM). The strengthening mechanism on the surface and sub-surface region due to the plastic deformation phenomenon caused by the impact of the pulsating jet was evaluated by Vickers microhardness test. The micro hardness test was conducted along the depth of the treated region to analyze the effects in the sub-surface layers. Also, the erosion stages at different standoff distance was evaluated by scanning the surface by optical MicroProf FRT profilometer in order to analyze the nature of erosion phenomenon with the variation of standoff distance and frequency during the treatment process. The results obtained indicates that the change in frequency of the pulsations and the variation in standoff distance has a significant impact on the surface integrity of the treated material. As compare to the untreated surface the hardness of the treated surface was increased up to a certain depth and the higher frequency of pulsations has shown better improvement in the hardness values. The above observations elaborated the effect of an important parameter frequency and standoff distance for better and effective utilization of the technology for the surface treatment application.

Keywords: Ultrasonic · Pulsed · Water jet · Erosion · Integrity
Micro hardness · Stainless steel · Non-Abrasive water jet

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1 Introduction

The striking advantages of water jet technology over the years makes it useful for wide areas of application like cutting, cleaning, surface layer removal, disintegration [1] etc. However, still the efforts are made to improve the performance of technology from the environmental and economical point of view [2]. With the recent growth and development in the industrialization and technologies, it has become essential to adopt a method which reduces the power consumption and cost while maintaining its quality. In view of this the water jet technology has undergone various modifications. In the recent years a new method of saving the energy and reducing the power consumption is adopted by increasing the efficiency of the jet in form of pressure pulsations. This method focusses on the generation of pulses via means of acoustic generators where the pressure pulsations are initiated by acoustic actuator present inside the acoustic chamber [3]. The acoustic actuator converts the electric power into mechanical vibrations and are amplified by the mechanical amplifier. These amplified vibrations are then transferred from the liquid waveguide to the nozzle system. The acoustic chamber is equipped with tunable resonant chamber for matching the natural frequency of the system to the frequency of pressure pulsations [3]. However, there are other methods adopted for pulse generation like nozzles integrated with mechanical devices, self-resonating nozzles and ultrasonic nozzles but these methods have certain disadvantages like the lifetime of the moving components in mechanical devices is low, in self-resonating nozzles low depth of modulations of a liquid jet is obtained and in ultrasonic nozzles high wear rate of the tip of the vibrating transformer and the increased weight of the cutting tool [3]. The method of generation pulsations by acoustic generator overcomes the above disadvantages. This method of pulse generation has been investigated for various applications in the recent years like disintegration of materials like copper [4], aluminium [5], bone cement [6], stainless steel [2], descaling applications [7], renovating of concrete surfaces [8], disintegration of rocks [9]. Foldyna et al. [2] studied the influence of pulsating water jet impact on the erosion pattern of austenitic stainless steel at an operating pressure of 10 MPa, 20 MPa and 30 MPa. A three stage erosion phenomenon occurred during the treatment process: in the first stage plastic or brittle deformation in the impacted zone occurs, in the second stage formation of erosion pits and its merging to form erosion crater takes place, in the third stage the depth of these craters increases. Foldyna et al. [5] also investigated the effect of pulsating water jet impact on aluminium surface where the aluminium sample surface was exposed to various pulsating jets under different operating conditions. The resulting surface was analyzed using optical microscopy and image analysis and was observed that pulsating water jet erodes aluminium surface deeply and effectively at a low pressure of 20 MPa. Klich et al. [10] also observed the effect of pulsating water jet on aluminium alloy with variously modified surfaces using fan jet nozzle of 2 mm diameter and 10° splash angle. The erosion of the surface layers were analyzed and its relation with the varying traverse speed at constant z = 55 mm was studied. The results obtained by surface roughness analysis showed that the initial surface properties has a significant effect on the final topography. While investigating the surface topography obtained by disintegrating the copper alloys (brass and bronze) using pulsating water jet [4] (using flat nozzle at a pressure of 40 MPa with z = 55 mm) it was observed that the average value of the roughness parameters was effected by the tensile strength and hardness value of the material. At higher traverse speed and number of transitions lower surface roughness was obtained in bronze however, in the case of brass at lower traverse speed and the lower number of transitions are suitable surface was obtained.

These applications majorly focused on understanding how variation in process parameters like jet pressure, traverse speed of the nozzle, diameter and geometry of the nozzle affects the performance of the technology and its comparison to the other technologies (continuous water jet, abrasive water jet) [11], but none of these studies focused on understanding the effect of variation of the standoff distance and frequency of pulsation during the treatment by ultrasonically generated pulsed water jet. The present study focusses on determining optimum standoff distance for the surface treatment application and also the effect of change in frequency of pulsation (which was encountered accidently during the treatment process) on the surface quality has been reported.

Initially, the erosion phenomenon on flat austenitic stainless steel (AISI 304) surface with the variation of standoff distance was explored by evaluating the depth of the treated region using optical MicroProf FRT profilometer. Further, the microstructural topography of the treated region at various standoff distances was observed under a scanning electron microscopy (SEM). The strengthening effect of the technology was evaluated by the micro hardness measurements which was conducted along the depth of the treated surface using Vickers micro hardness tester. Overall, this study elaborated the effect of an important parameters standoff distance and frequency of pulsations for better and effective utilization of the technology for the surface treatment application.

2 Materials and Methods

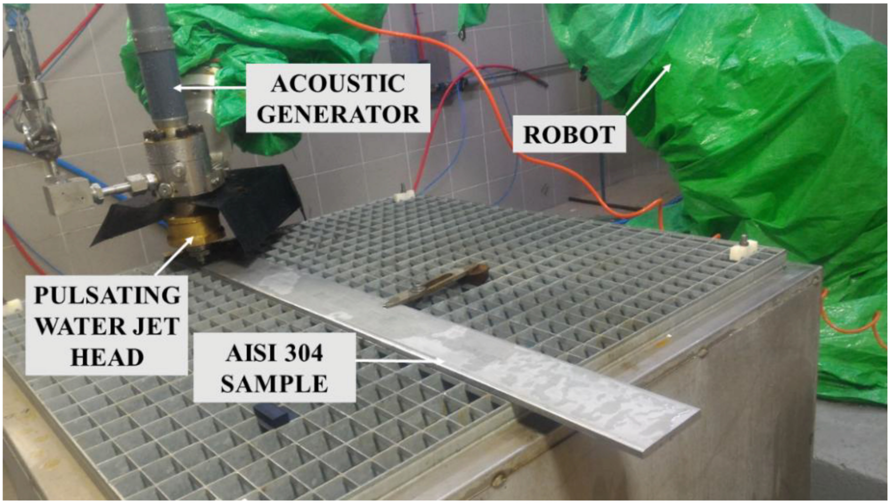
The austenitic stainless steel 304 grade was selected as the material due to its significant properties like corrosive resistance, high toughness, formability, ductility and drawability [12]. It is being used for wide applications in mechanical, automotive and nuclear industries [13]. The stainless steel of grade 304 has also its application in orthopedics, food and chemical processing industries [14].

The stainless steel AISI 304 sample of size 1000 mm × 100 mm × 10 mm having mechanical and chemical properties mentioned in Table 1 was subjected to the treatment process under pulsating water jet machine. The pulsating water jet machine constitutes: a HAMMELMANN HDP 253 plunger pump (maximum operating pressure of 250 MPa and flow rate of 40 l/min), an ABB robot IRB 6640–180/2.55 which controls the motion of the PWJ head, and an ultrasonic generator ECOSON WJ-UG-630-40 which contributes to the pulse generation.

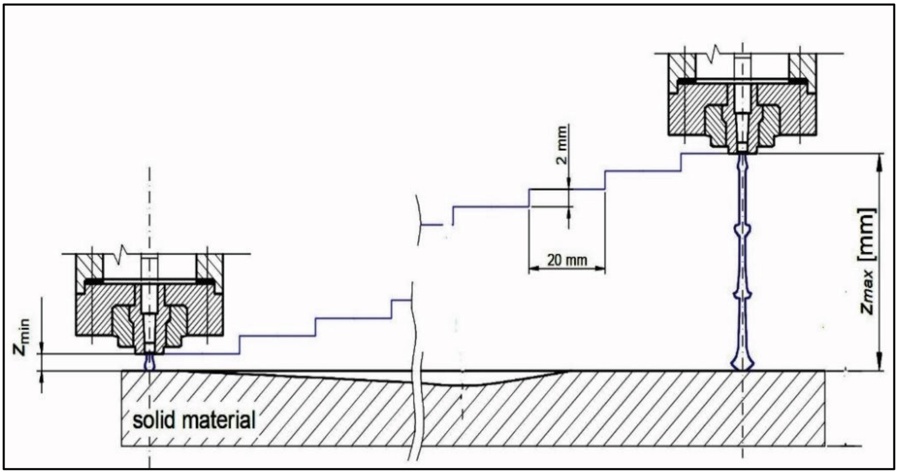
The sample was clamped on the working table with the pulsating water jet head positioning at 90° to the treated surface (Fig. 1(a)). The treatment was performed under the experimental conditions mentioned in Table 2 with variation in z from 5 mm to 101 mm (z changing by 2 mm at every 20 mm treated region) under each condition (Fig. 1(b)).

Table 1. Material composition and mechanical properties.

Material		
AISI 304	Chemical composition	C = 0.08%, Mn = 2%, Si = 1%, S = 0.03%, Cr = 18–20%, Ni = 8–10.5%, P = 0.04%
	Mechanical properties	(Hardness-Brinell) 88, μ = 0.27–0.3, E = 200 GPa, σ_t = 500 MPa, σ_K = 210 MPa, ductility = 45%



(a)



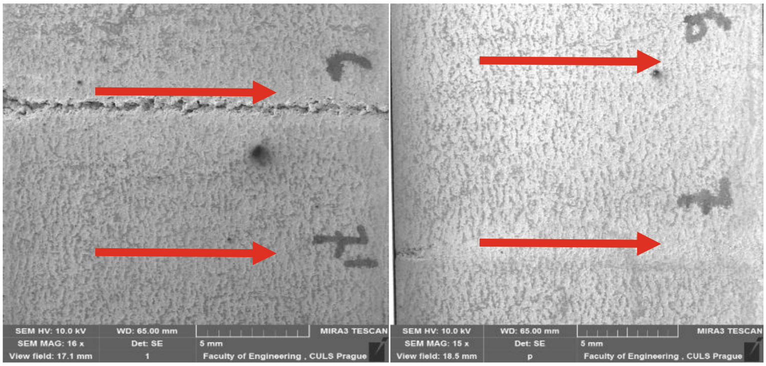
(b)

Fig. 1. (a) Experimental setup (b) Scheme adopted for treating the surface by varying the standoff distance from z_{min} (minimum standoff distance) to z_{max} (maximum standoff distance)

Table 2. Experimental Conditions.

S. No.	Nozzle type	d [mm]	p [MPa]	Amplitude [mm]	f [kHz]	Power [W]	v [mm/s]	z [mm]
1.	Circular	1.19	70	22	20.11	200	30	5–101 [with step distance of 2 mm]
2.					20.27	280		

In order to understand the erosion phenomenon under the subjected conditions the treated regions (Fig. 2) was scanned using optical MicroProf FRT profilometer and the depth of each region was evaluated using SPIP 6.6.1 software. The surface topography of the treated region was analyzed under a scanning electron microscopy (SEM). To determine the effect of this plastic deformation the hardness measurements along the depth of the treated region was conducted using Vickers Hardness testing machine Shimadzu HMV Micro Hardness Tester under a load of 50 g for 10 s.



(a) (b)

Fig. 2. Treated surface at (a) z = 43 mm (b) z = 71 mm.

3 Results and Discussion

3.1 Surface Erosion

The surface erosion plays an important role for the surface treatment application as it affects the service life of the material [15]. It significantly indicates the surface quality of the component. The treated surface shown in Fig. 2 was scanned using optical profilometer and the depth of the treated surface is evaluated using SPIP software. The plot between depth and standoff distance (Fig. 3) shows the nature of the impacting jet on the surface erosion of the material when the frequency of the pulsations was changed slightly. In both the conditions, the erosion phenomenon varied with standoff distance in various stages which shows that the frequency change has effect the erosion phenomenon. The initial stage of the impact showed no material loss up to z = 35 mm in case of lower frequency (20.11 kHz) and up to 55 mm in case of higher frequency (20.27 kHz). Further, as the standoff distance was increased an initiation in the material removal was observed which was plotted in terms of the depth of the surface generated. This removal of the material accelerated rapidly till it reaches its maximum value under each condition. The significant increase in the erosion effect was observed due to the impact of well developed pulses. Once the depth reaches its maximum value it started decreasing gradually. This nature could be attributed to diminishing effect of the pulses into the small droplets which is a result of the aerodynamic drag [5] which reduces the capacity of the pulsating water jet. With the further evolution in the erosion phenomenon on increasing the standoff distance no depths were observed on the treated surface.

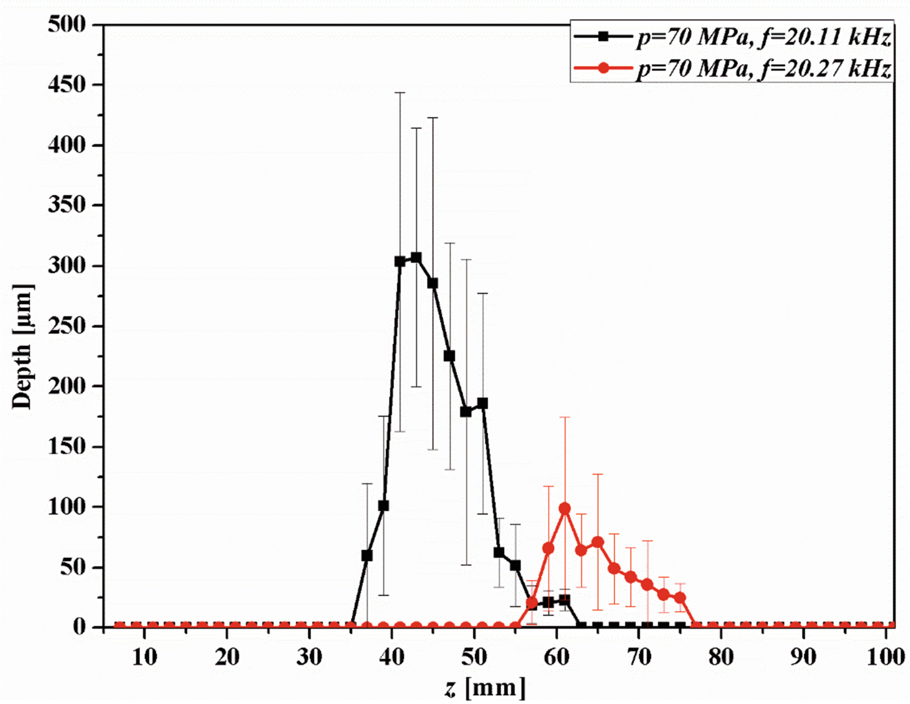


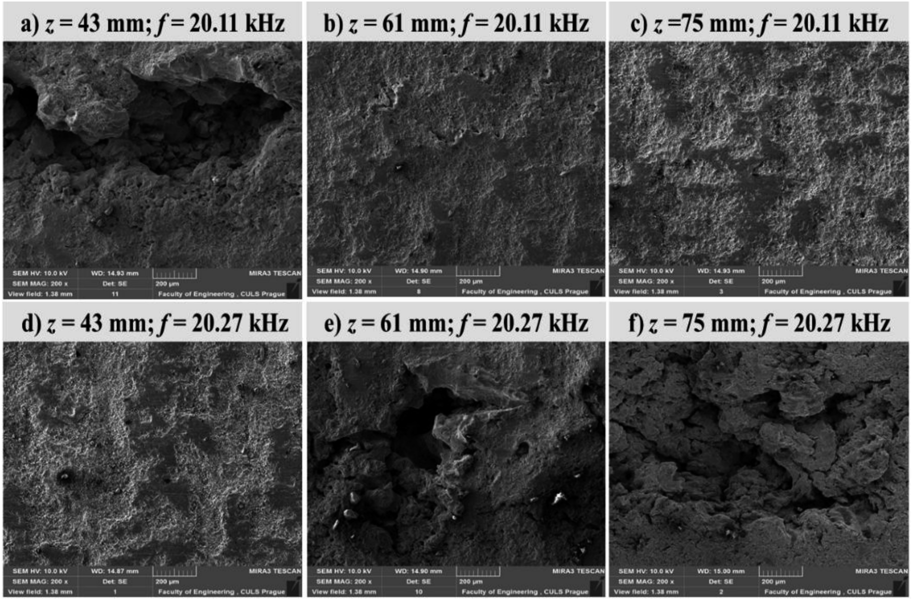
Fig. 3. Effect of variation of standoff distance on the surface treated with changing frequencies on depth of the treated surface.

It is evident from the plot Fig. 3 that the slight change in frequency effects the erosion phenomenon on the treated surface when the other parameters remains constant. In the region between z = 35 mm to 65 mm for the frequency of 20.11 kHz the erosion effect was prominent and for the frequency 20.27 kHz the z = 55 mm to 75 mm showed the erosion effect. The change in the range of erosion effect with the changing frequency is due to the break up length of the pulsating water jet i.e. with an increase in frequency pulses of shorter length will be produced [5]. The difference in the peak values of the depth obtained under both the frequency conditions is due to the effect of the striking pulse which hits with maximum energy at the peaks of the wavefront. In case of high frequency, $f = 20.27$ kHz the jet didn't strike the surface at the peak of the wavefront hence the depth obtained in this condition is low as compare to the depth obtained in low frequency ($f = 20.11$ kHz). The change in frequency encountered during the treatment process is potentially due to the wear of the sonotrode.

3.2 Microstructural Topography

From the above analysis the range of the standoff distance shows distinct regions of erosion. Instead of analyzing all the samples three samples were selected from the above range of z. Through the analysis of the microstructural topography of the treated surface the erosion phenomenon of the treatment process by pulsating water jet technology can be understood more widely. The several magnified images at selected locations at a magnification of 200 X is presented here. The Fig. 3 shows the surface topography of the samples treated under same conditions with slight variation in frequencies of 20.11 kHz and 20.27 kHz at $z = 43$ mm, 61 mm and 75 mm. It is evident from the Fig. 3 that the surface treated at a lower frequency (20.11 kHz) at smaller $z = 43$ mm shows the presence of deep depressions (Fig. 4(a)) at distinct locations was observed as the result of the surface erosion is caused by the well-developed impacting pulsed water jet. This is in corresponds to the depth vs standoff distance plot Fig. 3 where the maximum depth (307 μm) was obtained at $z = 43$ mm. These deep depressions indicate that the striking jet has enough impact force to cause serious plastic deformations on the surface which also affects the material quality. As the standoff distance was increased up to 61 mm these depressions disappeared but the even removal of the surface layers was observed (Fig. 4(b)). On further increase in $z = 75$ mm no deep depressions were observed rather a surface irregularity was generated (Fig. 4(c)) due to the diminishing effect of pulsed jet with droplets.

With the slight increase in the frequency to 20.27 kHz the surface topography under the same conditions as previous (other parameters remaining constant only z varies as 43 mm, 61 mm and 75 mm) changes. At the $z = 43$ mm some surface irregularities was observed (Fig. 4(d)) because of the nature of the impacting jet. In this range the cyclical impact of the pulse is not enough to exceed fracture strength of the material therefore, fewer deformations were observed on the surface. As the standoff distance was increased up to $z = 61$ mm, deep depressions appeared on the surface (Fig. 4(e)) due to the impact of well-developed pulsating jet. This can be related to the depth vs standoff distance plot (Fig. 3) obtained where the maximum depth (98 μm) was obtained at $z = 61$ mm. This signifies that the stream of pulsating water jet is capable of causing enough impact force to cause heavy deformations on the surface. With an increase of $z = 75$ mm large surface erosion (Fig. 4(f)) at a distinct location was observed. This is due to the fact that the shear stress developed by the cyclic impact of the pulsed water jet tends to exceed the fracture strength of the material, causing large erosion on the surface.



a) $z = 43$ mm; $f = 20.11$ kHz
b) $z = 61$ mm; $f = 20.11$ kHz
c) $z = 75$ mm; $f = 20.11$ kHz
d) $z = 43$ mm; $f = 20.27$ kHz
e) $z = 61$ mm; $f = 20.27$ kHz
f) $z = 75$ mm; $f = 20.27$ kHz

Fig. 4. SEM of the treated surface at p = 70 MPa, v = 30 mm.s^{-1}.

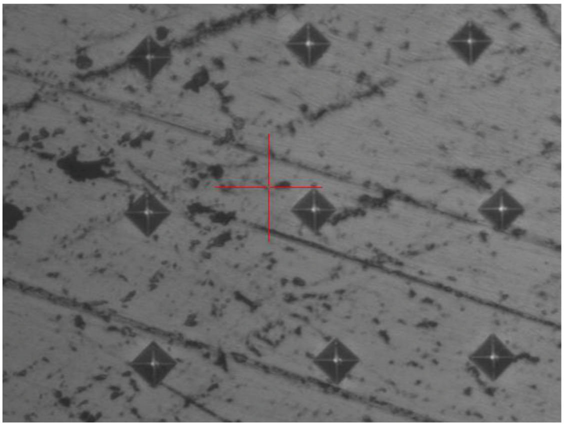


Fig. 5. Indentation points along the depth of the treated surface.

The changes in the microstructural topography observed with the variation in the standoff distance is attributed to the frequency of the impacting jet with high pressure.

3.3 Micro Hardness Measurements

The plastic deformation phenomenon occurring on the surface being impacted by pulsating water jet causes the hardening of the surface and near sub-surface layers. The effect of variation of standoff distance (at a pressure p = 70 MPa and traverse speed v = 30 mm/s) for both the frequencies was plotted as a function of depth along the treated surface (Figs. 6 and 7). The indentation points along the depth of the treated surface made during the measurements is shown in Fig. 5.

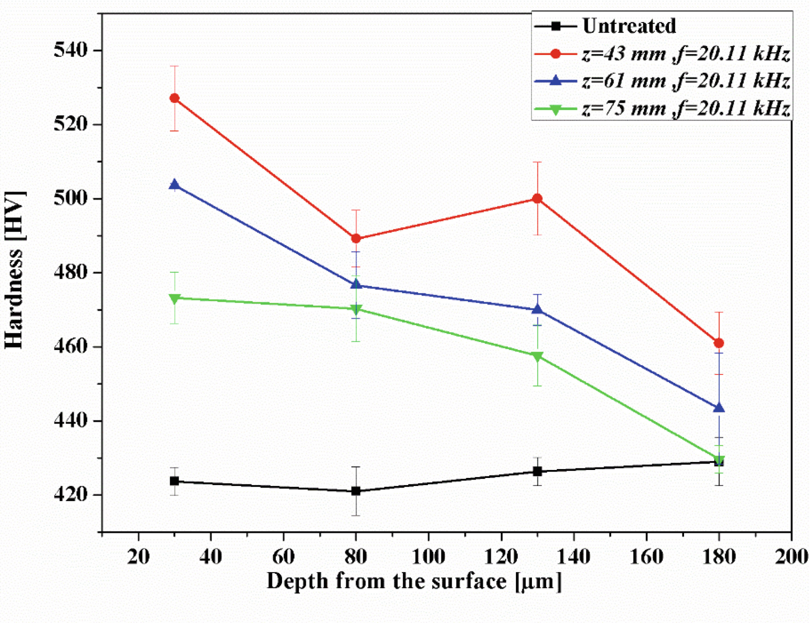


Fig. 6. Hardness measurements along the depth of the treated region at p = 70 MPa, v = 30 mm.s $^{-1}$, f = 20.11 kHz.

For both the frequencies as compare to the hardness of initial untreated sample there was a significant increase in the hardness observed after the treatment process by pulsating water jet. At the frequency of f = 20.11 kHz, up to the depth of approximately 180 μm there was an increase in the hardness values in the sub-surface layers with a maximum hardness of 503 HV at the depth of 30 μm. Also, it was observed that for lower z = 43 mm the maximum increase in the hardness was recorded. This is because the pulsations generated at this standoff distance are well developed and has sufficient impacting energy to cause large plastic deformation on the impacting surface and therefore, affecting its sub-surface layers. This observation is also very much evident from the surface topography at the z = 43 mm (Fig. 4(a)). Further, when the frequency of the pulsations was slightly increased to f = 20.27 kHz similar trend was observed as in the previous case. The increase in hardness was observed up to the depth of approximately 180 μm with maximum hardness recorded as 518 HV at the depth of 30 μm. However, no particular trend was observed with the variation of z. The maximum increase in the hardness was recorded at z = 61 mm. This again corresponds to

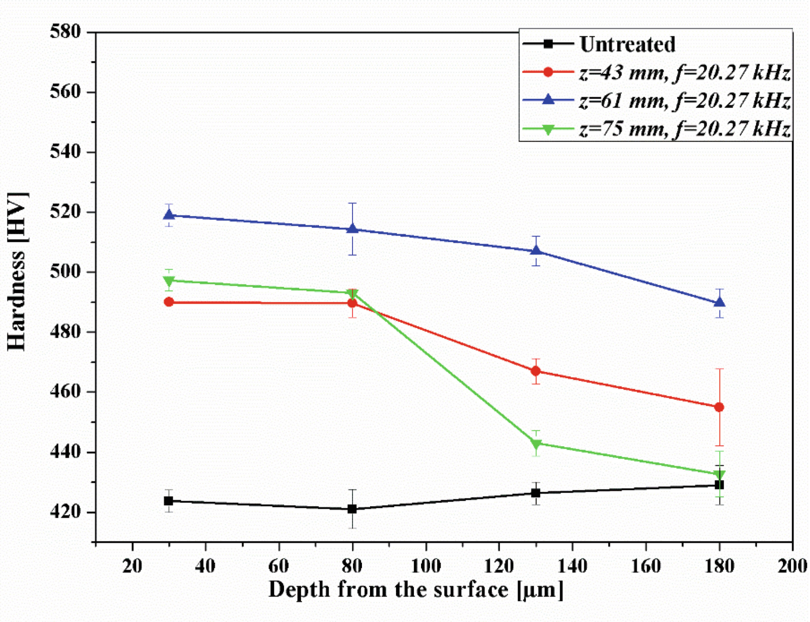


Fig. 7. Hardness measurements along the depth of the treated region at $p = 70$ MPa, $v = 30$ mm.s $^{-1}$, $f = 20.27$ kHz.

the surface topography of the region treated at $z = 61$ mm where the deep pits were observed due to the large plastic deformation caused by the impacting jets.

4 Conclusion

The work deals with an observational description of accidentally changed frequency. This study is an approach to determine the optimum standoff distance and also the effect of frequency of pulsations on the erosion phenomenon occurring during the treatment by pulsating water jet. From the present study following conclusions can be drawn:

- The change in frequency from $f = 20.11$ kHz to $f = 20.27$ kHz causes the change in the erosion phenomenon at different standoff distance (other conditions remaining constant). This is due to the shorter length of the pulses produced at a higher frequency.
- The surface quality of the material has been enhanced by the treatment of pulsating water jet and the frequency, standoff distance variation has shown a significant effect on its surface integrity. This frequency change faced during the treatment process was the result of the wear of the sonotrode.

- The different stages of erosion phenomenon observed during the variation of the standoff distance may be useful in determining the range of parameters for the surface treatment application.
- The microhardness of the sub-surface along the depth of the treated surface has been improved as compared to the initial hardness (423 HV) of the untreated surface. At frequency $f = 20.11$ kHz and $f = 20.27$ kHz, the maximum hardness values obtained were 518 HV and 503 HV respectively at the depth of 30 μm.

Till now not much study has been conducted on using pulsating water jet technology for the surface treatment application. This study gives a broader aspect of the variation of parameters like frequency and determining optimum standoff distance which will be helpful in determining the range parameters for the surface treatment application with minimal effect on surface roughness. Further, more variations in frequency parameter can be studied along with the variation in the pressure of the jet and traverse speed of the nozzle. This will be helpful in understanding the dependency of frequency parameter on the water jet process parameters.

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Abbreviations and Symbols

p -pressure [MPa]

v -traverse speed [mm.s $^{-1}$]

f -frequency [kHz]

d -diameter of nozzle [mm]

z -standoff distance [mm]

SEM -scanning electron microscopy

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