applied sciences

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A Comprehensive Study on the Challenges of Using Pure Water Jet as Post-Treatment of Abrasive Water Jet Milled Pockets in Titanium Alloy

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Abstract: Abrasive waterjet (AWJ) machining offers the possibility of creating a wide range of features on mechanical parts with different degrees of complexity with a relatively high efficiency. However, after the roughing passes, the surface quality of features such as blind pockets is rather low, with unfavorable implications for surface waviness and form deviations apart from high surface roughness. Apart from the traditional methods for finishing, such as grinding or lapping, it is worth attempting either to improve the surface quality obtained during roughing by an AWJ or to integrate a post-processing step by using a pure WJ in the existing process in order to ameliorate the surface quality. Thus, in the current study, the effect of pure waterjet (WJ) post-processing of machined pockets by AWJ milling on a Ti-6Al-4V workpiece using recycled glass beads was investigated under different conditions. The findings indicate that although the different post-processing treatments by a pure WJ can affect the surface quality on average, these differences are not considerably important, probably due to an insufficient capability of material removal, which hinders the smoothing effect on machined surfaces. Thus, it was indicated that a higher number of post-processing passes under different conditions than those of the roughing pass can be more favorable for efficient post-treatment by a pure WJ.

Keywords: AWJ milling; pocket milling; surface quality; waviness; post-processing; pure WJ; recycled glass beads

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Citation: Karkalos, N.E.; Karmiris-Obratański, P. A Comprehensive Study on the Challenges of Using Pure Water Jet as Post-Treatment of Abrasive Water Jet Milled Pockets in Titanium Alloy. *Appl. Sci.* **2024**, *14*, 1741. https://doi.org/10.3390/app14051741

Academic Editor: Giuseppe Lacidogna

Received: 30 December 2023
Revised: 6 February 2024
Accepted: 17 February 2024
Published: 21 February 2024

1. Introduction

Non-conventional techniques, usually employing a high energy beam, have revolutionized the manufacturing domain, as they have essentially enabled the rendering of various challenging features with higher efficiency and lower cost than conventional techniques [1]. Especially, in the case of hard-to-cut materials such as hardened steels, nickel superalloys, and titanium alloys, the use of non-conventional techniques can be beneficial as expensive machining setups, use of special cutting fluids, and assisted technologies can be avoided and the feasibility of the process is definitely increased. Moreover, as in the case of material removal processes, a high surface quality is a major requirement, and several non-conventional processes that have multiple capabilities in order to offer a considerably improved surface quality can be employed as an alternative to the traditional finishing processes.

Among the non-conventional machining processes, AWJ machining has attracted a lot of attention, especially regarding roughing of workpieces as it can achieve considerably high productivity, even for hard-to-cut materials such as hardened steels, titanium alloys, and nickel-based superalloys [2]. Moreover, it can be regarded as an eco-friendly process given that no harmful liquids are employed and no harmful gases are emitted during this process [3]. However, although AWJ machining is an inherently eco-friendly process, there is still the possibility for improvement in terms of sustainability indicators, something that can be achieved by not only maintaining high standards regarding environmental criteria but also considering the economic and social dimensions of sustainability. Actually, the sustainability of this process has been less frequently studied than the sustainability of other processes and the use of recycled, eco-friendly abrasives such as glass beads has been less reported in the relevant literature compared to conventional abrasives such as garnet, alumina, and silicon carbide.

Various types of features can be created by AWJ technology such as slots, contours, through cuts, holes, and pockets, among others [2]. Especially in the case of pockets it is important to choose appropriate process parameter values in order to obtain high dimensional accuracy and also acceptable levels of roughness and waviness. However, due to the intense nature of contact between the abrasive waterjet and the workpiece surface, the quality of roughed pockets is rather low and post-processing steps are required. Thus, pure WJ is preferred to be used in finishing operations, in order to avoid many shortcomings of the AWJ process, such as particle embedment [4], something that will be discussed afterwards [5].

Regarding post-processing, a pure WJ can be employed for polishing and other related purposes, such as deburring or cleaning. For example, Bergs et al. [6] employed a pure WJ for coating stripping and various researchers indicated that a pure WJ can be rather effective for paint removal, although an AWJ can more easily remove material, as the latter is associated with deterioration of the surface quality [7–9].

Several authors have employed a pure waterjet for other purposes as well, such as modification of the surface integrity. For example, various authors have studied the effect of a pure WJ treatment on the fatigue life of the processed surfaces. Azhari et al. [10] determined the effect of multiple WJ passes (up to six) on the surface quality, hardness, and fatigue life. It was shown that the surface roughness increased considerably with an increased number of passes and also the surface hardness had a notable increase. Moreover, although the compressive residual stresses increased in respect to the number of passes, the fatigue life was decreased. The same scientific group, in another study [11], also investigated the effect of WJ peening on stainless steel specimens by different strategies. They noted that every treatment led to a considerable increase of surface roughness, especially those including the fewest number of passes and the highest jet pressure, whereas a strategy including multiple passes with a gradually decreasing pressure was more beneficial. Consequently, this strategy also provided the highest hardening effect on the surface, being able to prolong the fatigue life as well. Boud et al. [12] found that although the surface quality deteriorated considerably after WJ processing, the fatigue life was able to be slightly improved in some cases, whereas this type of treatment was definitely useful for obtaining highly compressive residual stresses.

By using a carefully chosen jet path, the desired shape of the surface can be achieved without the use of a mask [13]. However, the efficiency of pure WJ and AWJ machining should be evaluated by multiple criteria, including not only surface roughness, texture, and integrity, but also geometrical accuracy [14]. Depending on the parameters chosen, a WJ can lead to significantly lower roughness, but in some cases, the difference between a WJ and AWJ is negligible [15]. Although some authors have investigated the appropriate conditions in order to minimize damage during AWJ processing of composites [16], a comparison regarding the use of an AWJ and a pure WJ for pocket milling of composite materials [17] pointed out that the jet energy and milling strategy were the most crucial parameters to be controlled in order to avoid fiber damage. Moreover, Monno and Ravasio [18] pointed out the influence of pressure fluctuations and vibrations on surface quality during AWJ use, concluding that pressure fluctuations only altered the depth of penetration, whereas vibrations were correlated with surface roughness.

Surface quality is also important for medical implants, as a specific level of roughness and texture is required in order to promote osseointegration and adsorption of substances [19,20]. More specifically, Sa, Ssk, Sal, and Sdr parameters were proven to be the most important for the characterization of biomedical surfaces, whereas jet pressure, standoff distance, and number of passes affected the nature of the surface, its height, and its waviness, respectively [21].

Apart from surface roughness, waviness should also be studied, as in the work of Adsul and Srinivasu [22] who conducted a comprehensive analysis of 2D and 3D roughness and waviness indicators during pocket milling of aluminum 6061-T6. Farayibi et al. [23] used a PWJ under two passes in order to improve the surface of a laser-clad titanium workpiece, showing a clear improvement in comparison to the use of electron beam irradiation, although the combined used of a PWJ and EBM did not provide any further improvement both for average roughness and waviness.

Moreover, the use of a plain WJ has proven to be beneficial in cases with a significant amount of embedded particles on the surface; thus, apart from surface quality and integrity, various authors attempted to address this major challenge in AWJ processes [24]. Bergs et al. [25] compared the effect of an AWJ, a WJ, and a WJ with suspension under two different levels of jet pressure, abrasive mass flow rate, and feed rate for two types of steel workpieces. It was shown that although the pocket depth was not considerably affected by the treatments, in some cases, a noticeable decrease in surface roughness was observed due to the release of embedded abrasive particles, chips, or damaged material from the workpiece. Furthermore, Schuler, Herrig, and Bergs [26] proposed a multi-stage processing of ceramic materials, including roughing with a hard abrasive and finishing with a much softer one. Their findings indicate that the use of the softer abrasive was beneficial as embedded particles were removed and the surface roughness was slightly improved.

Alberdi et al. [27] conducted a comprehensive work on the effect of a pure WJ treatment on the surface quality of specimens already machined by an AWJ. In their work, the jet pressure, traverse feed rate, stand-off distance, and number of passes were varied for the post-treatment stage, whereas for the abrasive waterjet experiments, a single pass was carried out, with abrasive mass flow rate as an additional variable. Regarding the AWJ treatment, it was proven efficient for the removal of embedded particles, and although in most cases, roughness was reduced, in some cases, a considerable increase was observed both in the longitudinal and traverse direction. Similar conclusions were drawn by Rivero et al. [28], who underlined that although a pure WJ can smooth out machined surfaces, low energy or exposure time should be avoided as the surface features produced by the previous step cannot be removed. However, a very low feed rate should also be avoided as the roughness produced under these conditions is comparable to or higher than that of AWJ milling.

Caro-Salinas et al. [29] conducted a comprehensive work on the effect of a plain WJ on the surface quality and integrity of the produced specimens. It was found that the grit embedment percentage becomes higher as the standoff distance increases and the jet pressure decreases, whereas the effect of the traverse feed rate was smaller. The surface roughness under pure WJ treatment was usually slightly higher due to the dislodgement of embedded particles, whereas the water droplets contributed to the smoothing of peaks to some extent. Moreover, the plain WJ treatment did not alter the residual stress distribution in most cases. Sourd et al. [30] conducted a thorough study on the effect of plain WJ cleaning on the removal of embedded grit and the surface quality of workpieces processed by an AWJ, indicating that water pressure is the most important parameter during cleaning and that this process can be very effective, leading up to 65% removal of embedded particles. Furthermore, one sustainable solution is the use of soluble abrasives in order to avoid the problem of particle embedment, which reduces fatigue life and poses challenges to the application of coatings, while they also offer a better material removal rate (MRR) than a plain WJ [31]. Finally, regarding the processing of implant materials, another option is the use of biocompatible abrasives, which were shown to produce surfaces with higher quality than those processed by a pure WJ, but are related to low MRR values [32].

Among the variants of pure WJ processing apart from a pure WJ, Mitchell, Sadek, and Kinsey recently proposed water droplet machining by means of a Rayleigh jet [33,34] in order to avoid delamination when cutting composites, but at the expense of using low traverse rates. Another alternative type of WJ processing involves the combined use of water and air jets, based on the concept of a “fuzzy jet” [35] or injection principle (iAWJ) [36]. In general, the use of air, which is injected in the WJ, can be used as an additional factor that is regulated to achieve superior performance. Moreover, another alternative for improving fatigue life is to use ultrasonic pulsed WJ (PWJ) in order to enhance the effect of impact on the workpiece surface. Although the surface quality after the treatment deteriorated with Ra values up to almost 35 μm for low traverse speeds, compressive stresses were developed, up to 345 MPa near the surface, thus improving the surface integrity [37]. In general, the use of a pulsating water jet can lead to alteration of the workpiece microstructure by modifying the geometry of the grains and increasing their misorientation to a large extent compared to the use of a continuous WJ. Furthermore, the surface quality deteriorates more rapidly with the use of a PWJ compared to a continuous WJ [38].

Nag et al. [39] also proposed the use of a pulsating WJ as a more efficient way for material processing and tested this process under different pressures, nozzle diameters, and time durations. Their analysis showed that apart from the differences in obtained depth, higher pressures and the use of PWJ led to a higher increase in the surface hardness. Finally, Wang et al. [40] employed a multi-jet polishing technique in order to improve the quality of additively manufactured parts and found that this method could lead to even nanometric-level roughness.

Given that only a few works performed a comprehensive analysis on the effect of different conditions of pure WJ treatments and a literature gap is identified both regarding the effect of pure WJ treatments on multiple surface roughness indicators and surface waviness, as well as regarding the efficiency of post-process treatments using a pure WJ for pockets machined by recycled glass beads, it was considered important to carry out a relevant study. Thus, in this work, AWJ milling experiments were carried out in order to create rectangular pockets on Ti6Al4V workpieces and a pure WJ treatment under different conditions was subsequently performed in order to study its effect on surface quality based on multiple indicators. The practical use of this work is mainly related to an evaluation of the limitations of the use of a pure WJ as a post-treatment method and to indicate possible strategies that can improve its capabilities for developing a superior surface.

2. Materials and Methods

2.1. Scope of the Present Work

The subject of this work is related to the investigation of the effect of pure WJ treatments on the morphology of surfaces processed by AWJs. Although several studies were conducted on this subject, a comprehensive analysis under different conditions based on multiple metrics of surface quality is still lacking, something that will be briefly explained afterwards.

At first, it should be mentioned that although a pure WJ can definitely impact softer materials such as polymers, it does not provide the capability for material removal in the case of metals and ceramics but can be recommended for the purpose of cleaning or peening, e.g., for altering the surface integrity and prolonging fatigue life, without inducing further morphological changes, something that became evident from the literature review.

However, despite a pure WJ having several advantages over an AWJ for finishing operations, several challenges were pointed out regarding its use. Among others, the anticipated low material removal rate, which is not a requirement for finishing but can restrict its capabilities to remove the irregular features of the workpiece surface at least in a small number of passes, and the possibility of increasing the surface roughness due to improper choice of process parameters are drawbacks that should be further studied in order to be able to choose appropriate strategies.

The literature review indicated that already, a considerable amount of work has been dedicated to the effect of pure WJ treatments on surface integrity and the elimination of particle embedment from the machined surface. However, only a few studies have analyzed the effect of pure WJ treatments on surface roughness indicators apart from Ra and Rz, and its effect on waviness is rarely reported. Thus, the present work aimed to shed light on the implications of pure WJ treatments on morphological alterations of the workpiece surface based on multiple metrics for surface roughness, including average waviness as well as an investigation of the variation of these values, which is widely neglected in the relevant literature, with many works not even reporting the variation, which can be considerable and is representative of the uniformity of the surface profile over the pocket area.

2.2. Experimental Details

In the present work, AWJ pocket milling experiments were carried out under two different process conditions with a view to determining the effect of post-process treatment by a pure waterjet on the surface quality of the produced pockets. Various post-process treatment strategies were tested and evaluated based on multiple criteria in order to determine whether they had a noticeable difference in the quality of the produced pocket surfaces. More specifically, the details of the different treatments are presented in Table 1.

Table 1. Details of the two series of experiments carried out in the present work.

Series	No.	Type of Pass	Passes	Jet Pressure (MPa)	Abrasive Mass Flow Rate (g/s)	Traverse Feed Rate (mm/min)
1	1	Roughing	1	200	2	800
1	2	Finishing	1	200	0	800
1	3	Finishing	2	200	0	800
1	4	Finishing	1	200	0	400
1	5	Finishing	1	200	0	1600
2	1	Roughing	1	200	1	800
2	2	Finishing	2	200	0	800
2	3	Finishing	3	200	0	800
2	4	Finishing	2	200	0	400
2	5	Finishing	2	200	0	1600

As can be seen from Table 1, 4 different treatments were tested for each different process condition. The first pass, which was used for the creation of the pocket (roughing) was normally conducted by the use of an abrasive waterjet, and the subsequent pass or passes were performed only by a waterjet. The parameters that were varied were the number of passes and the traverse feed rate of the waterjet. In the case of the first series of experiments, the roughing pass was conducted under a waterjet pressure of 200 MPa, an abrasive mass flow rate of 2 g/s, and a traverse feed rate of 800 mm/min. Then, the first treatment was performed by conducting a single finishing pass with a pure WJ under the same jet pressure and traverse feed rate as the roughing pass, and the second treatment included an additional identical pass in order to determine the effect of the number of passes on surface quality. Finally, the third treatment was performed at a traverse feed rate reduced by 50%, and the fourth treatment was performed under a traverse feed rate increased by a factor of 2 in order to determine the effect of the traverse feed rate on the surface quality. In the case of the second series, the abrasive mass flow rate was reduced to 1 g/s and the same pure WJ treatments were applied, but in every case, an additional pass was performed in order to determine the effect of a higher number of passes. Although the conditions during the roughing pass were different, some qualitative conclusions could be definitely deduced. The parameters that were kept constant during the experiments included the standoff distance (3 mm), jet impingement angle (90°), and stepover (0.4 mm). Moreover, the orifice diameter was 0.3 mm, the nozzle diameter was 1.0 mm, and the focusing tube length was 76.2 mm. The overall procedure carried out in the present work is depicted in the schematic of Figure 1.

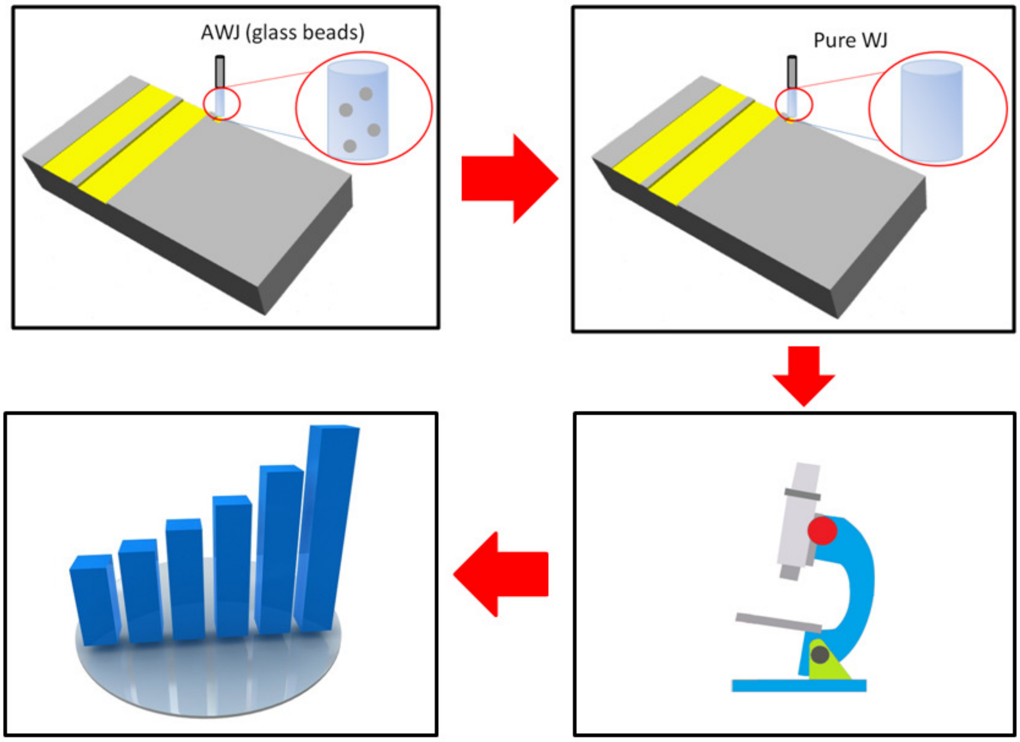


Figure 1. Outline of the present work.

All of the experiments were carried out on a model HWE-1520 H.G. RIDDER Automatisierungs GmbH machine (H.G. RIDDER H., Hamm, Germany) machine tool, shown in Figure 2, with capabilities of regulating the jet pressure between 50 and 400 MPa and an abrasive mass flow rate between 10 g/min and 600 g/min (0.167 g/s to 10 g/s), and also offering a wide range of traverse feed rates, controlled by a Siemens (Munich, Germany) SINUMERIK system. The abrasive material used for the experiments was recycled glass beads with a mean diameter of 292.62 μm and a distribution indicated more clearly in the graph of Figure 3, hardness of 6.5 on the Mohs scale, and composition as shown in Table 2, based on the specifications of the manufacturer. In every case, the milling strategy for the pockets was a zig-zag i.e., straight paths with alternating directions under the same nominal traverse feed rate. The nominal dimensions of the pockets were 30 mm in length and 9.6 mm in width. Given the relatively lower hardness of the abrasive material in comparison to the hardness of common abrasives, e.g., garnet, Al_2O_3, and silicon carbide, it was anticipated that the wear of the nozzle could be rather minimal; however, the nozzle diameter was checked before the experiment and after some passes in order to verify this assumption. Finally, the workpiece material was Ti-6Al-4V alloy (titanium grade 5), with its composition presented in Table 3. It is worth noting that this material has already been used in AWJ experiments [41,42] but research on the machining of pockets with an eco-friendly abrasive on this material is limited.

Table 2. Chemical composition of abrasive material.

SiO_2 (%)	Na_2O (%)	CaO (%)	MgO (%)	Al_2O_3 (%)	Fe_2O_3 (%)	TiO_2 (%)
70.0–73.0	13.0–15.0	7.00–11.0	3.00–5.00	0.50–2.00	0.1	0.1

Table 3. Chemical composition of workpiece material.

Ti (%)	Al (%)	V (%)	Fe (%)	C (%)	Sn (%)	Si (%)	Nb (%)
90.0	5.48	4.22	0.112	0.1	0.0625	0.0222	0.0386

Figure 2. Waterjet machine tool employed for the experiments.

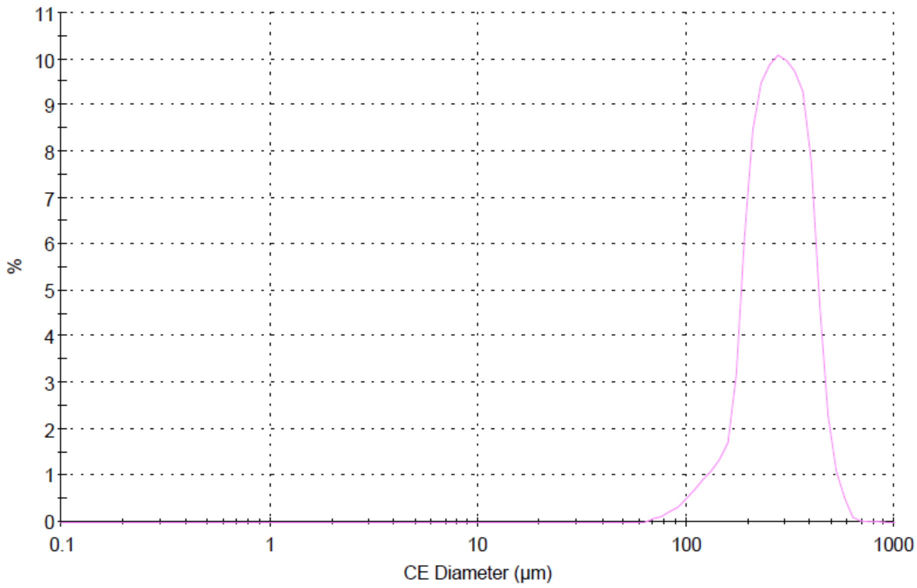


Figure 3. Abrasive particle diameter distribution.

After the experiments were conducted, several measurements were performed on the produced pockets. At first, the depth of the pockets was estimated by repeated measurements on a coordinate measuring machine (CMM), namely a Mitutoyo CMM Crysta Plus M443 (Mitutoyo, Kawasaki, Japan). The measurement of surface quality indicators was performed by using a VHX-7000 ultra-deep-field microscope (KEYENCE, Mechelen, Belgium), which is a focus variation microscope with the capability of zooming up to 2000×. Its function is comparable to that of confocal microscopes and a white light LED source is employed that passes through a semi-transparent mirror and a lens before eventually reaching the surface of the measured object. A mirror-like component termed a beam splitter redirects the light that bounces back from the focal points to an optical sensor, where it is recorded both spatially and in terms of brightness using a light-sensitive device.

By combining the narrow depth of field typical of traditional optical systems with vertical scanning, FV (focus variation) technology is able to produce high-resolution, colorful 3D surface measurements at a lower cost. Since a 4K camera was employed, the resulting images had a resolution of 4096 $\times$ 2160 pixels.

Using these 2D images, it was possible to measure the various surface quality indicators along multiple lines in order to obtain averaged values. More specifically, for every pocket the following indicators were recorded: Ra, Rz, Rp, Rv, Rsk, Rku, and Wa. Ra represents the average surface roughness, which is defined as the arithmetic average of the profile height deviations from the mean line, whereas Rz is defined as the maximum peak-to-valley height of the profile. Moreover, Rp and Rv represent the maximum peak height above the mean and maximum valley depth below the main line, respectively, while Rsk represents the skewness, e.g., asymmetry of the profile about the mean line and Rku represents the kurtosis e.g., intensity of features of the profile about the mean line. Finally, Wa is the average surface waviness, which is a higher order deviation (i.e.,a longer wavelength) than the surface roughness.

For each indicator of surface roughness, the measurement was conducted on a sufficiently long path on the pocket surface including multiple evaluation lengths in order to achieve a reliable result, as the measurement of a restricted part of the surface, as was conducted in other studies, may lead to misleading results without generality. The cutoff (denoted as λc) for the filtering of the roughness profile was selected based on the ISO 4288-1996 standard [43] determined by the Ra values. As the Ra exceeded 10 μm in every case, λc was selected as 8 mm and the evaluation length 40 mm. For every quantity, average values are presented as well as the values of the coefficient of variation (CV), defined as the ratio of the standard deviation of the measurement σ to the average value μ.

3. Results and Discussion

3.1. Pocket Morphology and Average Depth

In Figure 4a–f, the morphology of the produced pockets for some indicative cases of both series of experiments is depicted. These images were created based on the 3D reconstruction of the pocket surface by the focus variation microscope and allow for a comprehensive qualitative evaluation of the morphology of the created pockets, as they represent the whole pocket area in real color.

From the figures relevant to the first series of experiments, it can be seen that the surface of the first pocket seems to lack very deep marks or signs of grooves produced by the movement of the abrasive waterjet, apart from the obvious curvature of the profile near the walls of the pocket. However, there are several flat regions that are separated from the other regions by noticeable lines on most of the pocket surface. On the other hand, the morphology of the pockets treated by a pure WJ is obviously different. The main characteristic of the pockets produced after the four different treatments is the higher irregularity of the surface. From Figure 4b, regarding the third pocket, it was observed that the surface contains numerous shallow circular marks that dominate the surface, probably created either by dislodged embedded particles or by removing material between formerly merged impact sites of abrasives. Although there are other small differences such as the depth of the pockets or some areas with different inclinations, the four pockets that were processed by the pure WJ appear to have the same texture. The same situation also appears in the case of the second series of experiments, with all treated pockets including numerous circular marks on their surface. Despite the fact that the quantitative analysis of the following sections can reveal more details about the differences in the produced texture, it can be concluded that the effect of the pure WJ treatment under the selected conditions definitely alters not only the surface quality of the grooves but also the texture of the surface, probably as the impact of water on the surface can smooth some of the peaks produced by the abrasive, or dislodge some embedded particles, revealing new patterns on the surface.

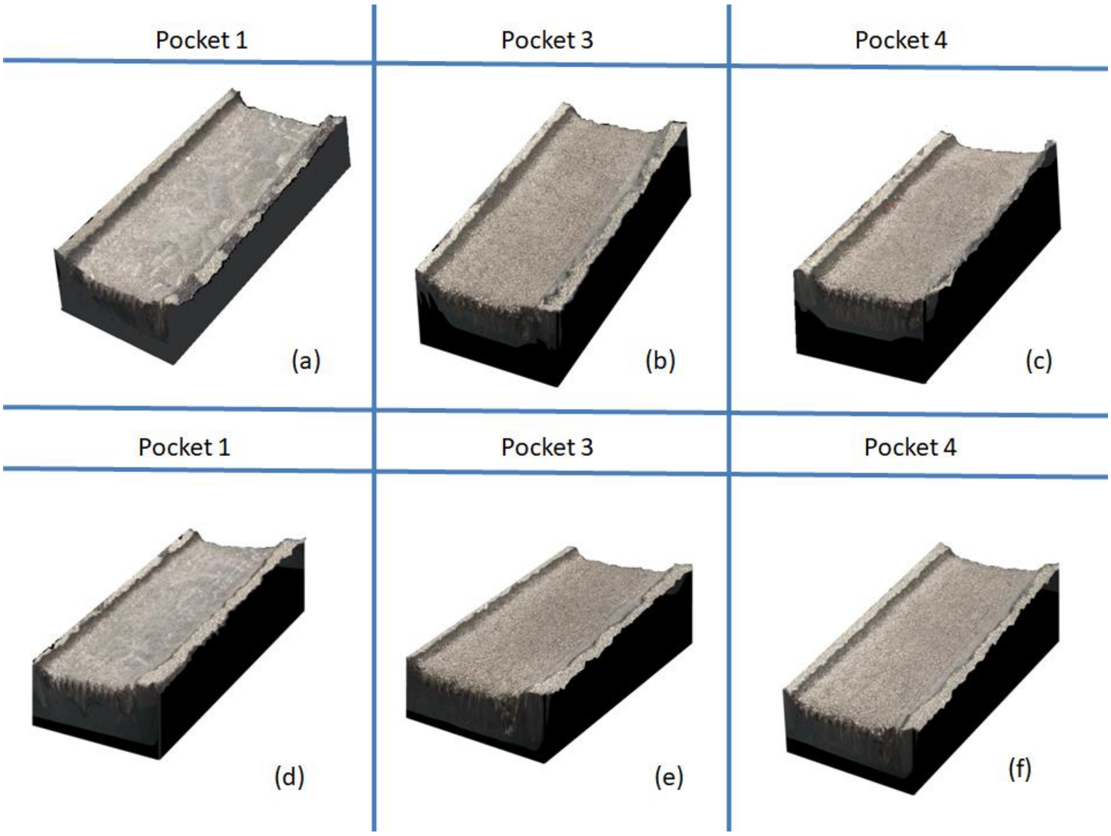
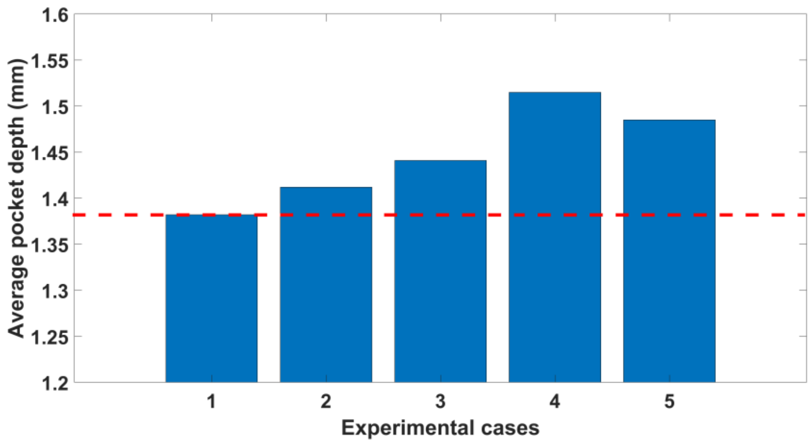


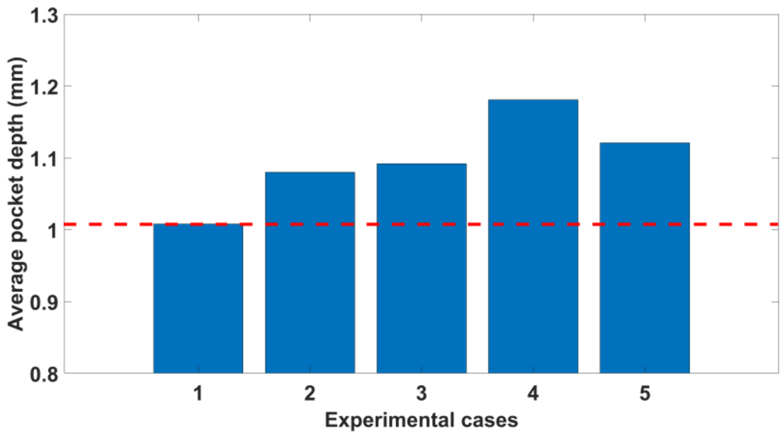
Figure 4. 3D images of the produced pockets from the two series of experiments: (**a**) Series 1—1st pocket, (**b**) series 1—3rd pocket, (**c**) series 1—4th pocket, (**d**) series 2—1st pocket, (**e**) series 2—3rd pocket, (**f**) series 2—4th pocket.

Apart from the discussion of pocket morphology, as part of the general evaluation, the depth of the pockets was measured by CMM and will be briefly discussed afterwards. The average depth of the pockets was evaluated for each different condition and the results are displayed in Figure 5. This information is rather important as the effect of the pure WJ on material removal during the post-process treatment can be determined. The results indicate that the anticipated correlation can be established between the process parameters and the pocket depth, although the amount of removed material is minimal compared to the amount of material removed during the roughing pass. For the first series of experiments, the depth increased when a single pass of pure WJ was carried out and it was further increased by the second subsequent pass. Moreover, the use of a lower traverse feed rate for the WJ produced a higher depth due to a higher exposure time, whereas the use of a much higher speed led to a less noticeable increase in depth.

Similar observations can be conducted regarding the results of the second series of experiments, although the depth values are slightly lower due to the lower value of the abrasive mass flow rate. These observations are essential in order to understand the impact of the pure WJ on the surface roughness as the amount of removed material can be correlated with the alteration of existing peaks on the surface, which in turn affects various surface roughness indicators, something that will be discussed afterwards in Section 3.2. It is important to note that given that the differences in average depth are comparable to the Ra and Rz values, the variation of depth will have a prominent impact on the obtained surface quality.



(**a**)



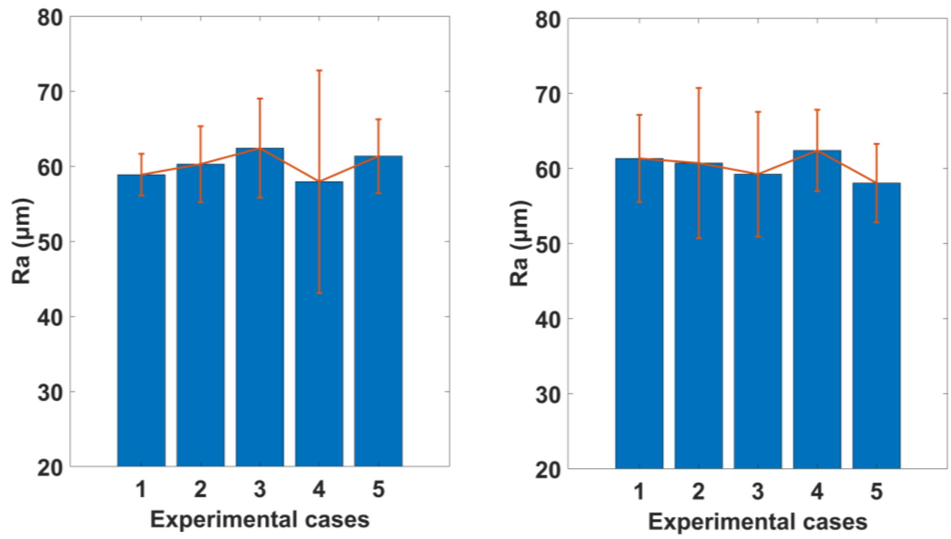
(**b**)

Figure 5. Average depth of the produced pockets: (**a**) First series of experiments and (**b**) second series of experiments. The red line indicates the average pocket depth after the roughing stages in both cases.

3.2. Analysis of Surface Topography of the Produced Pockets

3.2.1. Results Regarding Ra and Rz

After the experiments were conducted, the surface roughness indicators were measured using the focus variation microscope, with the Ra values presented in Figure 6. For the first series of experiments, the use of a single pass of a pure WJ at the same traverse feed rate as the roughing operation led to a slight increase in the average value of Ra. This can be explained due to the material removal process during the finishing pass. In fact, the small amount of material removal by the pure waterjet, less than 50 μm, as can be observed in Figure 5a, led to the revealing of small circular marks produced by the part of the spherical glass beads that penetrated the surface, something that was not observed in the case of the AWJ operation, where only larger and relatively flatter regions appeared on the surface, probably due to the merging of adjacent impact sites. The use of a second WJ pass contributed to a further minor increase of Ra, as the depth was further decreased by a few tens of micrometers, increasing the size of the marks produced by the first finishing pass. Thus, it is indicated that this number of passes under the specific process conditions was not sufficient to totally smooth out the marks from the roughing process. However, given the high variability of average roughness, these differences can be regarded as negligible on average. Similar results indicating the inefficiency of a pure WJ treatment in various cases and even deterioration of the surface quality were also observed in the relevant literature [9,25,29–32,37], compared to both polished and roughed pockets. Among the most probable reasons for the inefficiency of a pure WJ treatment, it was also suggested that the energy of the jet and exposure time can play a considerable role as they can regulate the material removal process for eliminating peaks on the surface, whereas inappropriate values of the process parameters may introduce new peaks, thus deteriorating the surface quality [28,38,44].



(**a**) (**b**)

Figure 6. Ra values for (**a**) the first and (**b**) the second series of experiments.

The relatively high values of average roughness can be attributed especially to the waterjet pressure and stepover employed during the roughing pass. Regarding the effect of the waterjet traverse speed during the post-processing operation, although it was expected that an increase of speed can lead to a better surface quality [15,24], an increase of surface roughness was observed. This phenomenon can be attributed to the fact that the faster speed of the jet, related directly to a lower exposure time, was not sufficient to appropriately smooth the remaining peaks, thus creating a less regular surface, with a slightly high roughness and a higher average depth of cut, which in turn led to an increase of the average height peaks and valleys on the pocket surface.

Regarding the second series of experiments, the use of an additional post-treatment step showed some signs of improvement in the average values of surface roughness. More specifically, the Ra values were reduced when two pure WJ passes were used after the roughing pass and further reduced with a third pass. In this case, the traverse feed rate also exhibited the anticipated trend, with only a small reduction in surface roughness after two passes of WJ at a smaller speed but a considerable decrease of surface roughness at a higher traverse speed. Although the variation of roughness values was still high in order for the average values for each treatment to be significant, the trend of average values showed slightly better results for the second series of experiments. In particular, the use of multiple passes, even under different conditions, was also shown to have beneficial results in other works [10,11]. In general, the surface roughness values were similar to those of the first series of experiments due to the low contribution of the abrasive mass flow rate as a factor regarding surface roughness; in fact, the magnitude of roughness was not significantly altered, as it is mainly regulated by the jet pressure, stepover, and traverse feed rate during the roughing stage.

Another important indicator, which is not mentioned in the relevant literature, is the uniformity of the roughness on the pocket surface. As in the present study, the roughness was measured along multiple parallel lines, the coefficient of variation (CV) values for Ra can be estimated as the ratio of the standard deviation to the average value of Ra and be used as an indicator of the uniformity of the roughness profiles on the pocket surface. From the results presented in Figure 7a, it becomes obvious that the use of a pure WJ leads to a higher deviation of surface roughness across the pockets. The highest value of CV was observed for the fourth case, for which the longest exposure time was used, indicating that the pure WJ treatment can have a detrimental effect on the uniformity of surface quality, above the acceptable level of 0.1 or 10%, when improper parameters are employed. An interesting finding is that the use of a higher traverse feed, related to the lowest exposure time, was related to a higher degree of uniformity, although the nominal value of Ra was not improved. Regarding the results presented in Figure 7b, it can be seen that the use of a pure WJ decreased the level of uniformity of the surface roughness, but the use of a higher traverse speed for the post-treatment led to a comparable level of uniformity in respect to the roughing pass. Finally, the relatively higher values of CV for the second series of experiments can be attributed to the lower abrasive mass flow rate, which is related to a lower probability of fracture of the abrasive particles, thus creating a more irregular topography.

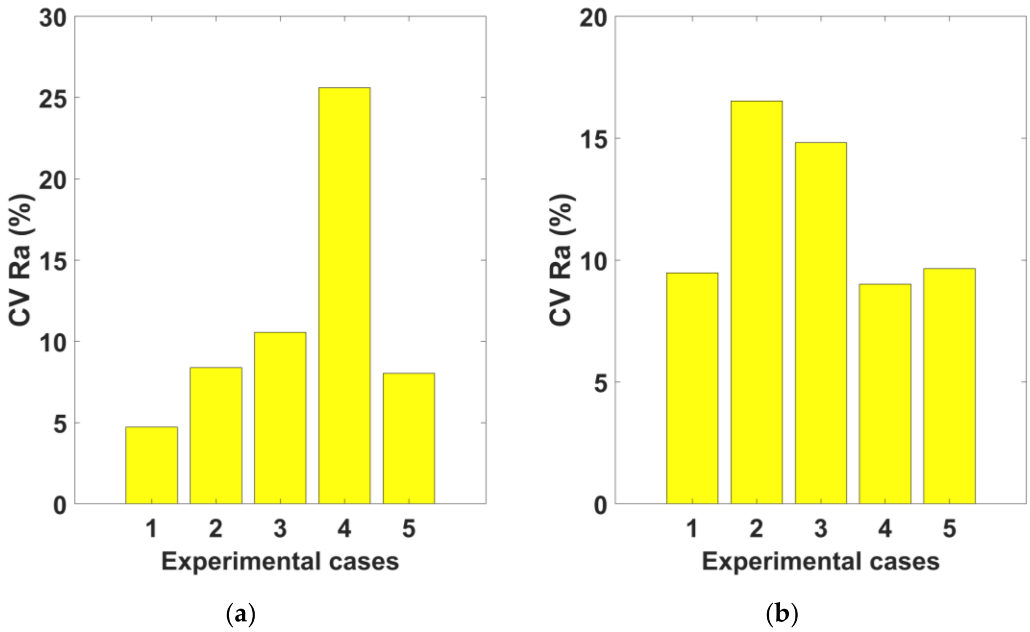
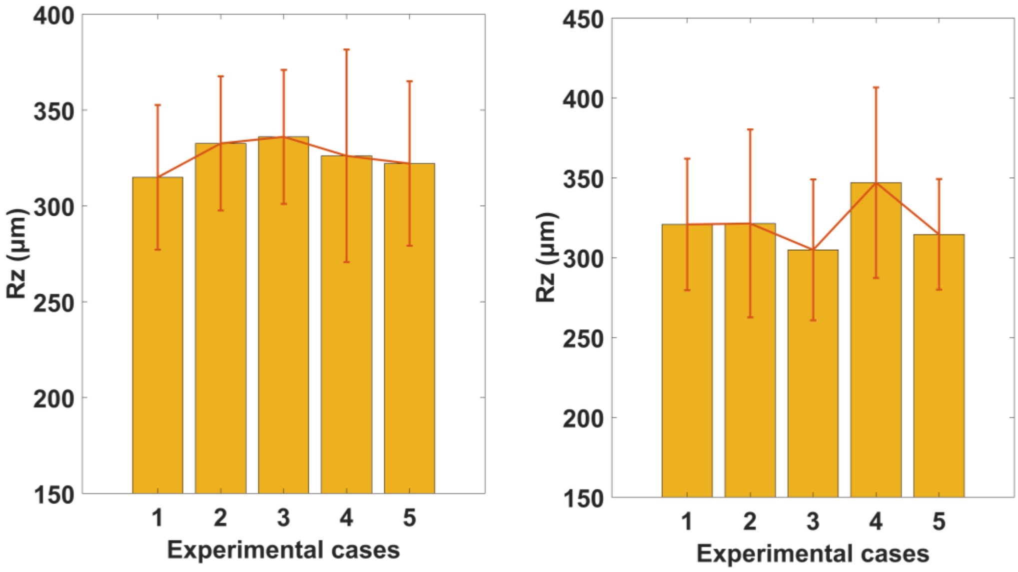


Figure 7. CV values for Ra for (**a**) the first and (**b**) the second series of experiments.

Apart from Ra, it is important to discuss briefly the findings regarding Rz. Usually, the values of this parameter vary in the same way as the values of Ra and thus, similar conclusions can be expected. However, in the present case, it is important to observe the magnitude of Rz in respect to the variation of the depth of pockets after a pure WJ treatment in order to further explain the findings. In Figure 8, the variation of Rz in respect to different pure WJ treatments for the two different series of experiments is depicted. As can be seen, the use of a pure WJ increased Rz, both for one and two passes. The use of a different speed led to a slight reduction of Rz, especially at the higher traverse feed rate. In the second series of experiments, although the use of two passes led to an almost identical average Rz, the use of three passes showed an indication of improvement. However, the use of a lower traverse rate clearly led to a higher Rz, whereas the use of a higher traverse rate reduced Rz, as was anticipated.

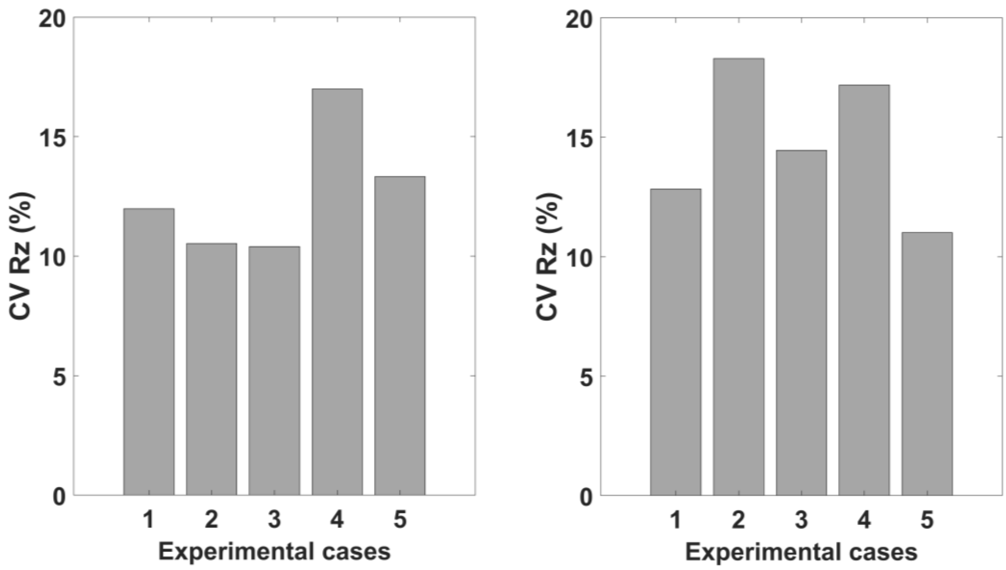
In conclusion, despite the considerable variation of Rz values, based on the average values it can be seen that there are many similarities with the variation of Ra and that the value of the total height of the roughness profile is significantly higher than the additional depth of material removed by the pure WJ. The last observation was further investigated by directly analyzing the values of Rp and Rv, as discussed in the following subsection.



(**a**) (**b**)

Figure 8. Rz values for (**a**) the first and (**b**) the second series of experiments.

In the case of Rz, the values of CV, as can be seem in Figure 9, exhibit generally higher values than Ra and are less divergent between different treatments. As in the case of Ra, the highest CV value was observed for the case with the lowest traverse feed rate for the first series of experiments, whereas in the second series of experiments, the highest number of passes and the highest traverse feed led to higher degree of uniformity in the Rz values of the produced pocket surface.



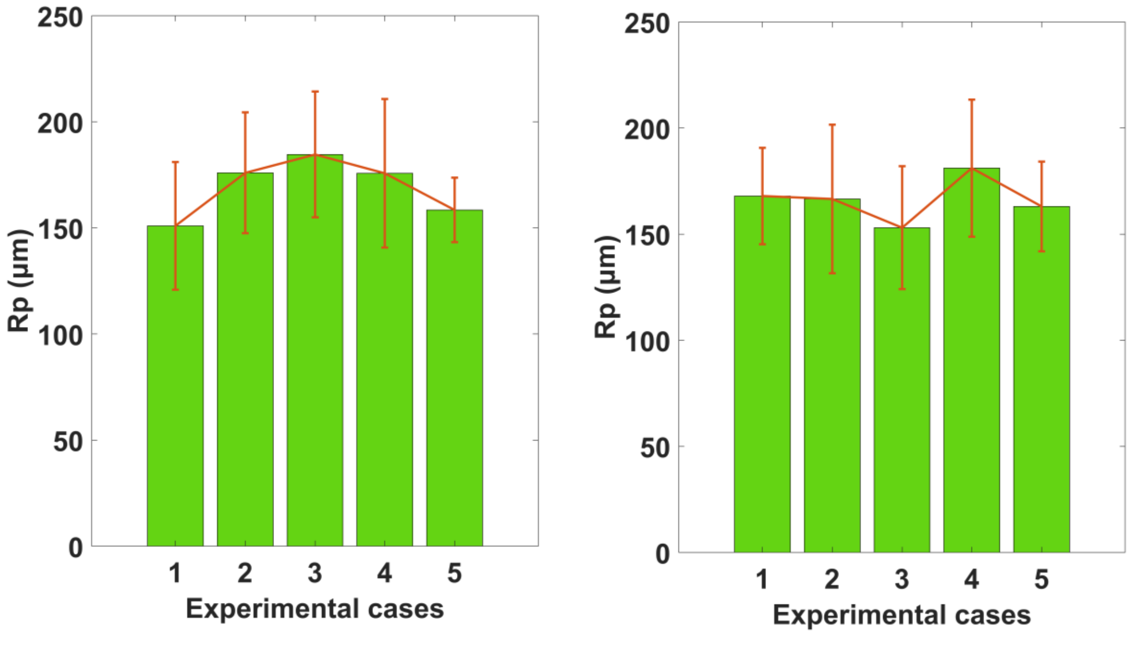
(**a**) (**b**)

Figure 9. CV values for Rz for (**a**) the first and (**b**) the second series of experiments.

As a general conclusion, it can be deduced that the surface roughness exhibits rather negligible differences due to the pure WJ treatment for the two different series of experiments studied. The differences between the average values of Ra and Rz indicate that the number of passes or traverse feed rate can yield slight explainable variations but the variability of results indicates that it is not possible to considerably alter the surface roughness by a pure WJ treatment unless different strategies are applied.

3.2.2. Results Regarding Rp, Rv, and Wa

Apart from the analysis of the Ra and Rz values, it is worth analyzing the values of Rp, and Rv, as well as the surface waviness values, in order to gain a deeper insight into the effect of a pure WJ post-treatment on the surface topography. Especially, the measurement of peaks and valleys in the roughness profile is essential in order to further understand the effect of material removal during a pure WJ treatment on the obtained roughness. Regarding Rp, the results depicted in Figure 10 indicate that the height of peaks in the roughness profile increases with the number of passes, proving that the low amount of material removal during a pure WJ treatment compared to the peak height after the roughing stage (30–133 μm at most, compared to almost 150 μm) is not sufficient to smooth considerably the peaks of the surface, resulting probably only in separating the impact sites of abrasive particles, creating microscopic channels between them but not eliminating them. That is the reason why a pure WJ treatment is not effective regarding the decrease of Ra. Moreover, the additional plastic deformation exerted on the workpiece may further deteriorate the surface quality. In both series of experiments, similar trends were observed regarding the effect of the traverse feed rate, whereas in the second series of experiments, the increase of passes above two provided a lower Rp due to the higher amount of material removed in this case, which eventually reached half of the value of Rp in this case. Given the level of variability of the results, the differences between various treatments are again not considerably significant but at least the analysis of Rp values has managed to provide a plausible explanation for the inefficiency of pure WJ treatments regarding surface roughness.



(**a**) (**b**)

Figure 10. Rp values for (**a**) the first and (**b**) the second series of experiments.

In Figure 11, the depth of the valleys of the roughness profile can be observed. In several cases, the values are comparable to those of Rp, something that will be later explained by the analysis of the Rsk and Rku indicators. In the case of Rv, it is not expected that similar trends can be observed as in the other indicators given that the valley depth cannot be influenced in the same way as the peaks. In that case, the increase in the number of passes led to a decrease of valley depth, probably due to material removal, which lowered the level of the pocket bottom. Moreover, the probable separation of merged abrasive impact sites on the surface of the pockets leaves void regions between them and water from the jet further reduces the level of the pocket bottom, creating a larger difference between the highest peaks and the lowest valleys. On the contrary, the effect of the traverse feed rate is totally negligible, both regarding the average and standard deviation values of Rv, but in the first series of experiments, using a different traverse feed rate value than the traverse feed rate used for roughing provided a lower Rv.

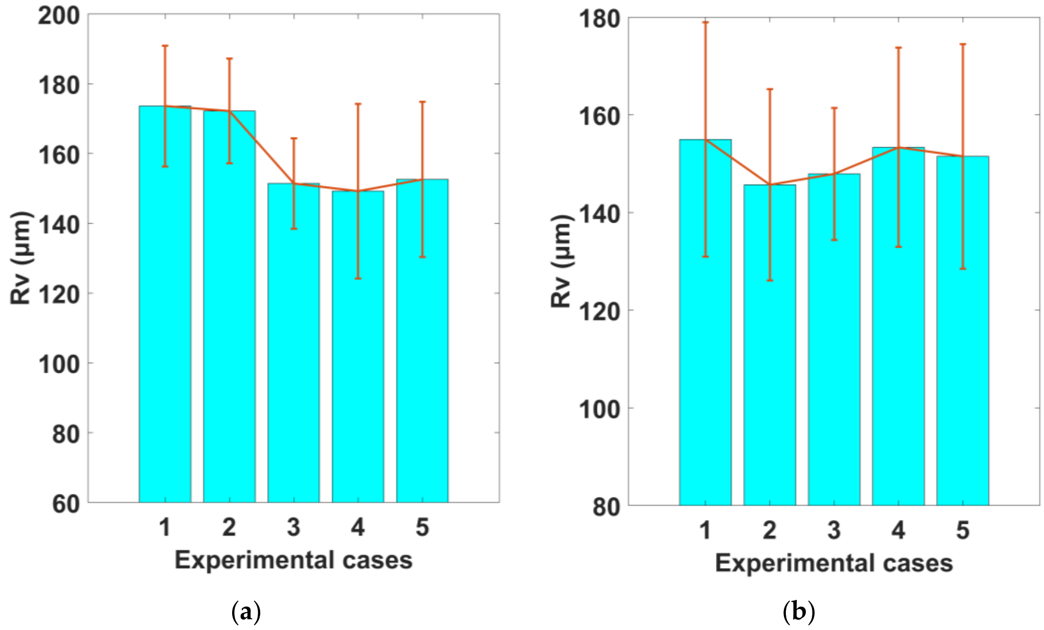
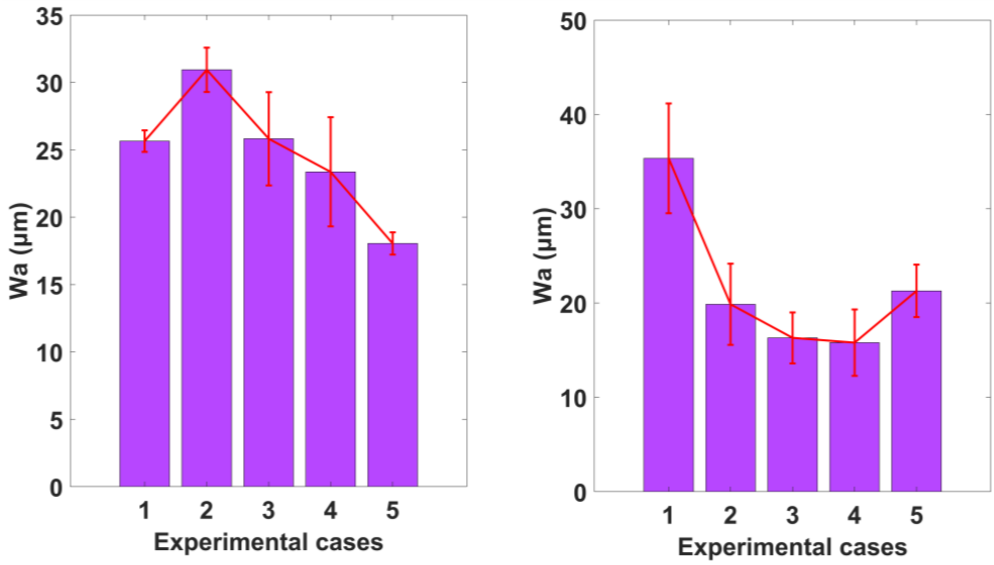


Figure 11. Rv values for (**a**) the first and (**b**) the second series of experiments.

Apart from the surface roughness indicators, the waviness of a surface can be an important consideration during the evaluation of surface quality. Although it is associated with longer wavelength irregularities of the machined surfaces, it also affects the functionality of the surface and its wear behavior. This quantity it is rarely studied in machining processes as it cannot be directly correlated with process parameters in the same way as surface roughness; however, it can provide additional insight into the effect of different post-treatments on the machined surface. In the present work, the Wa indicator was measured in all cases, and the results are depicted in Figure 12. In general, the results reveal a noticeable difference in most cases than that observed regarding the surface roughness. Especially in the first series of experiments, the use of an additional pass using WJ with the same traverse feed rate as the roughing stage led to an increase in waviness, but the use of an additional step or the use of a different traverse feed produced a lower waviness value, even lower than the initial one. Regarding the second series of experiments, it was found that the use of an additional step of pure WJ treatment was beneficial in every case, with waviness decreasing to values lower than the initial one. This result implies that the waviness of the surface can be more easily regulated by using pure WJ treatments, especially with a higher number of passes, although the effect of the traverse feed rate is less evident. These observations are in line with the results of Farayibi et al. [23], who also found a considerable reduction of Wa after pure WJ treatment.

3.2.3. Analysis of the Rsk–Rku Topological Map

Finally, after analyzing the results of various surface roughness and waviness indicators, it is important to take into account more advanced surface roughness indicators as well in order to be able to detect potential changes in the functional properties of the surface, including tribological and corrosion characteristics of the surface. In practice, these parameters are useful in order to determine the oil retention capabilities or friction properties of surfaces, something that cannot be determined by simple roughness parameters [45–47]. Especially, Rsk and Rku are related to the tribological characteristics of the surface and are usually analyzed in a common Rsk–Rku topological map [48,49], such as the one in Figure 13. From these results, it can be observed that regarding the first series of experiments, the use of a pure WJ clearly affected the skewness of the surface by exhibiting more positive values, i.e., more pronounced peaks than deep valleys, as was also observed in the Rp and Rv results, due to the inefficient removal of peaks. However, in the second series of experiments, given that a surface with positive skewness was obtained by the roughing stage, the differences were lower after the pure WJ treatment and larger deviations occurred only regarding kurtosis. Such surfaces often indicate a higher friction coefficient and lower oil retention capabilities [48,49]. Moreover, in most cases, the kurtosis of the roughness profile increased, indicating a more Gaussian-shaped height distribution with less deviation around the mean.



(**a**) (**b**)

Figure 12. Wa values for (**a**) the first and (**b**) the second series of experiments.

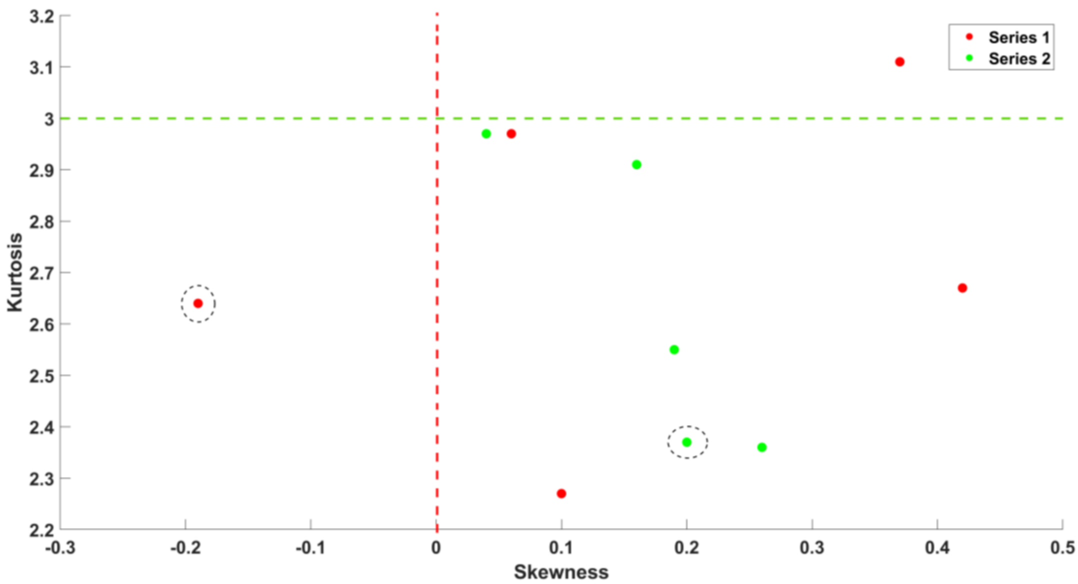


Figure 13. Rsk–Rku topological map for both series of experiments. The dotted circles denote the (Rsk, Rku) pair values for the roughing pass for each series of experiments.

4. Conclusions

In the present study, a comprehensive study on the determination of the effect of a pure WJ treatment on the surface quality of pockets milled by AWJ technology was carried out. Different conditions were tested based on a different number of pure WJ passes and traverse feed rate values, and two different series of experiments were carried out depending on different roughing conditions. After the results were analyzed, several conclusions were drawn.

The average surface roughness and maximum dimension of the profile cannot be effectively reduced by one or two pure WJ passes, especially under the same traverse feed rate as the roughing step. Although the average values of Ra and Rz vary in respect to both the number of passes and the traverse feed rate, their variation along the pocket surface is relatively high in most cases, indicating that a pure WJ treatment cannot be considered capable of improving the surface quality with a simple machining strategy.

The analysis of Rp and Rv revealed that a plausible reason for the inefficiency of the pure WJ treatment was that the additional depth of pocket removed by the pure WJ was much lower than the size of the peaks, leading to only partial removal of the peaks and probable separation of the previously merged impact sites, thus maintaining or even increasing the average roughness of the surface, as well as the peak height. Moreover, the action of the waterjet in void regions between the impact sites can further increase the difference between the highest peaks and lowest valleys, thus increasing Rz.

Waviness of the surface was the only quantity that was shown to be positively affected by the pure WJ treatment, as it could be decreased after subsequent pure WJ passes, especially in the second series of experiments. Thus, it can be deduced that a pure WJ treatment under the tested conditions is more favorable for higher-order surface deviations.

The analysis of the Rsk–Rku topological map indicated that a pure WJ treatment on average increased the skewness and kurtosis of the surface so that a surface with dominant peaks occurred, probably increasing the friction coefficient and lowering the oil retention capability, something that was implied by the greater impact of a pure WJ treatment on the average Rp than the Rv values.

Finally, the findings of this work can provide useful suggestions for the improvement of the efficiency of a pure WJ treatment. It is advised that further research on the use of different milling strategies, e.g., adopting multiple WJ passes, should be carried out in order to appropriately regulate the jet pressure and stepover apart from the traverse feed rate in order to remove a larger amount of material and effectively remove larger peaks without leading to further deterioration of the surface by plastic deformation. Thus, it is possible to use a pure WJ treatment as an eco-friendly and low-cost means of pocket finishing.

Author Contributions: Conceptualization, N.E.K. and P.K.-O.; methodology, N.E.K. and P.K.-O.; software, N.E.K.; validation, N.E.K.; formal analysis, N.E.K.; investigation, N.E.K.; resources, P.K.-O.; data curation, N.E.K.; writing—original draft preparation, N.E.K. and P.K.-O.; writing—review and editing, N.E.K.; visualization, N.E.K.; supervision, N.E.K. and P.K.-O.; project administration, N.E.K. and P.K.-O.; funding acquisition, N.E.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Polish National Agency for Academic Exchange (NAWA, Agreement No. BPN/ULM/2022/1/00129/U/00001).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors would like to sincerely thank Tymoteusz Turlej regarding the determination of the diameter distribution of abrasive particles used in the present work.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of the data; in the writing of the manuscript; or in the decision to publish the results.

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