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ORIGINAL ARTICLE

Effect of Waterjet Cleaning Parameters During Paint Removal Operation on Automotive Steel Components

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ABSTRACT – The automotive industry is expanding quickly, and each year, many vehicles are produced with beautiful paints. Increases in the number of end-of-life or old vehicles will occur as a result of uncontrolled growth in the number of manufactured vehicles. Recycling car parts is therefore necessary in the automotive industry specially to beautify the appearance of old vehicles with new paint. Waterjet cleaning is one of the most contemporary techniques frequently employed to guarantee uniform paint removal with no secondary pollutions. Study on waterjet cleaning parameters mostly focuses on pressure, traverse rate, and standoff distance. However, there are other new parameters associated with waterjet cleaning process namely number of cleaning passes and overlap rate which shows improvement in paint removal but lack in literature reviews. In the present study, paint is removed using the abrasive waterjet (AWJ) and plain waterjet (PWJ) paint removal techniques from parts made for automobiles in order to examine cleaning characteristics such as effectiveness and surface roughness. The findings indicated that AWJ cleaning process was more effective at cleaning than PWJ, which had a smaller cleaning capacity. However, AWJ cleaning process resulted in a rougher surface due to complete removal of paints as well as erosion of the substrate material. A better control of AWJ cleaning process may result in more efficient of paint removal without damaging the substrate material.

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INTRODUCTION

The automotive industry, among the world's largest sectors, is undergoing a rapid expansion on an unprecedented rate of growth. A variety of products and components are produced by the automotive industries. Because of the uncontrolled increase in the number of manufactured automobiles, the automotive industry is required to recycle car components. Reusing and recycling these parts in the automotive industry is a standard operation that begins with removing the paint from the components [1]. Cleaning with efficient paint removal and minimal environmental impact is one of the primary areas of focus for paint removal operations of automobile components. A common practice to remove paint is by using traditional methods which are chemical and mechanical cleaning. However, these methods have limitations, such as labor-intensiveness, energy loss, expense, component degradation, and waste management. Alternative methods, such as waterjet cleaning and laser cleaning, are non-traditional methods that have been developed. The most popular cleaning method is laser cleaning since it is so convenient, but it has drawbacks, including a risk to public health. In order to overcome the drawback of laser cleaning, waterjet cleaning offers a promising and possibly successful paint removal method with minimal substrate damage. There are various mechanical cleaning processes like sandblasting, water brushing, low-pressure water spray, hydropneumatic cleaning, and controlled dry sanding. However, these methods are not as eco-friendly as waterjet cleaning. This has led to an increase in the popularity of waterjet cleaning. The waterjet method offers no health risks like gas, dust, or odors when compared to other traditional cleaning methods like mechanical and chemical methods [2][3]. Since water is the medium used in the waterjet process, there is no heat effect when compared to other cleaning methods like plasma or laser cleaning, which can cause the substrate to melt or burn due to high heat affection [4][5].

The input parameters for the waterjet, including pressure (P), standoff distance (s), traverse speed (t), and feed rate (u) among others, all have a major influence on the amount of debris that is removed during the cleaning process. In order to define the process output for the WJ application, the waterjet input parameter is adjusted. Due to the influence of its input settings, the use of a waterjet to remove paint causes a variation in the surface's topography of the material being machined [6][7]. A crucial component of the cleaning process is the pressurized water of the water jet; this water's energy is transformed into kinetic energy as it passes through the orifice and creates a high-velocity jet [8][9]. As the amount of pressure and paint erosion in the targeted area increases, a greater amount of energy will be required to remove the paint. Additionally, it was discovered that there are 15 standoff distances that, when used optimally, provide the maximum possible paint loss [6].

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The experimental design for AWJ and PWJ cleaning on stainless steel material painted with automotive paint in the study that has been presented uses a full factorial method. The cleaning efficiency and surface roughness of the AWJ and PWJ characteristics are analyzed. The cleaning efficiency of the AWJ and PWJ cleaning operations is investigated.

RELATED WORK

Material

The material is painted mild steel which measuring 50 mm × 25 mm × 5 mm in dimension as shown in Figure 1. Instead of actual car parts, designed pieces were used to simplify the experiment. An automotive paint that mimicked the properties of car parts was applied to the substrates. Prior to painting, the substrate had an average surface roughness (R_a) of about 1.2837 m, and after painting, it had an average R_a of about 0.8742 The mechanical parameters of the paint that was applied to the substrate are outlined in Table 1.

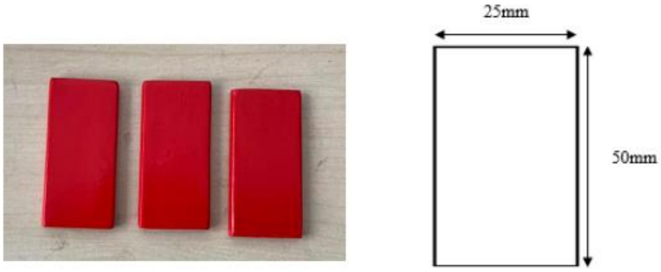

Figure 1. Part shape and dimensions.

Table 1. Mechanical Properties of paint of on the substrate.

Paint	Elastic Modulus, *E* (GPa)	Yield strength, $\sigma_{0.2}$ (MPa)	Ultimate strength, σ_b (MPa)
Top coating	1.59-1.76	11.34-15.85	17.43-21.22
Intermediate coating	1.54-1.88	8.99-13.10	10.71-13.75
Primer	0.52-0.77	4.93-7.11	7.83-10.60

Equipment

Throughout the entirety of the experiment, a waterjet machine that had been self-developed and was capable of producing up to 100 MPa of water pressure was utilized. The pressure was generated by an air-driven liquid pump, and a Computer Numerical control (CNC) system was also attached in order to regulate the movement of the waterjet system's nozzles. Both of these components worked together to provide the desired effect. The movement was managed and controlled along various axes (X and Y), and it also had the ability to move along the Z-axis (depth) in order to adjust the standoff distance. The cutting head contains a ruby orifice that is 0.127 millimeters in diameter, as well as a tungsten carbide focusing tube that measures 76.2 millimeters in length and has a diameter of 0.76 millimeters. The CNC waterjet machine that was self-developed is depicted in Figure 2, along with an illustration of each component.

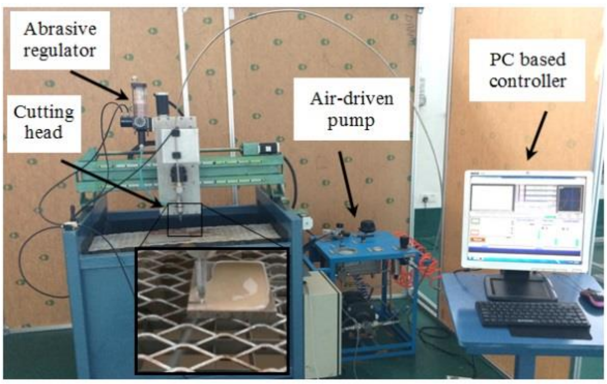

Figure 2. The self-developed waterjet machine is attached to the CNC system.

Experimental Design

The selected design of the experiment followed a fractional factorial (3^3). Table 2 illustrates the use of three factors with three levels for each: pressure (*P*), number of passes (*n*), and overlap (*O*). It is crucial to note that the standoff distance (*SOD*) remained fixed at 50 mm because a change in standoff distance has a considerable impact on surface roughness when the overlap distance changes [10][11]. To maintain consistent surface roughness (Ra) across the entire surface, the traverse speed was kept constant at 90 mm/min. This is because the traverse rate plays a crucial role in determining surface roughness, and as it increases, so does the R_a. [12]. The orifice size and impact angle were both kept at a consistent value of 90 ° and 0.127 mm throughout each and every trial. On the waterjet machine table, the sample was appropriately arranged to be clamped as shown in Figure 3. According to NC code, the waterjet nozzle was programmed to move in the *y* and *x* axes. During the process of traversing the nozzle across the entire width of the sample, a series of water-generated impacts that overlapped each other were used to clear the covering region.

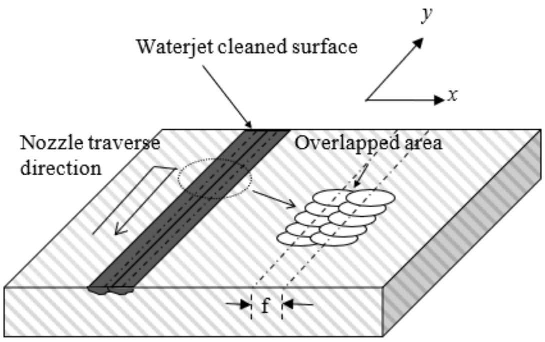

Figure 3. schematic representation of the process of paint removal using a waterjet.

In accordance with the overall factorial design of the experiment, a series of 14 experimental runs were executed utilising a constant abrasive flow rate of 2 g/s for AWJ cleaning and PWJ cleaning. Each run consisted of cleaning the AWJ and PWJ. Tables 3 and 4 display the experimental design with surface roughness and cleaning efficiency results.

Table 2. Input parameters and the levels of those parameters.

Machining Parameters	Number of levels	Values
Pressure, *p* (*MPa*)	3	21, 41, 62
Number of passes (*n*)	3	1, 2, 3
Overlap, *O (%)*	3	25, 50, 75

Table 3. Experimental layout for AWJ cleaning.

Run	Pressure (*P*)	Number of passes (*n*)	Overlap (*O%)*	Roughness (R_a)	Cleaning efficiency (%)
1	21	2	50	3.6357	21.9
2	41	1	50	5.0595	22.24
3	41	2	25	4.9552	30.43
4	41	2	50	3.649	26.47
5	41	2	75	5.2042	23.44
6	41	3	50	3.7863	25.79
7	62	2	50	4.7142	25.98

Table 4. Experimental layout for PWJ cleaning.

Run	Pressure (*P*)	Number of passes (*n*)	Overlap (*O%)*	Roughness (R_a)	Cleaning efficiency (%)
1	21	2	50	2.2457	1.05
2	41	1	50	3.6243	1.05
3	41	2	25	3.7402	1.58
4	41	2	50	5.7912	1.28
5	41	2	75	3.6575	1.3
6	41	3	50	2.136	1.4
7	62	2	50	0.549	1.54

For PWJ and AWJ cleaning, the overlapping distance was calculated using the cleaning width of the generated pressure for each of its three stages at a constant SOD of 50 mm. For PWJ, the average cleaning with is 0.651 mm for 21 MPa, 0.906 mm for 41MPa and 1.129 mm for 62MPa. For AWJ, the average cleaning with is 6.30 mm for 21MPa, 8.50 mm for 41MPa and 8.70 mm for 62MPa.

For the purpose of determining the area's surface roughness, an OLS5000 laser confocal microscope was utilised. It can measure a range of sample kinds precisely in three dimensions. In addition to this, it has the ability to select measurement areas in order to complete fundamental analytical tasks which are determining area, step size, line width, topography, surface roughness, and volume. In terms of paint removal, cleaning efficiency is the cleaning capability for both PWJ and AWJ. Using MATLAB software, the cleaning efficieny was determined after measuring the surface roughness. It was acquired by image processing and MATLAB software's segmentation of the machined area from photos of the machined samples. To prevent underestimating the cleaning capacity, the pictures of each sample were acquired at a fixed resolution of 1000 x 500 pixels.

EXPERIMENTAL RESULTS

Effect of waterjet input parameter on Surface Area Roughness

The analysis of the effect of waterjet pressure on the mean surface area roughness of plain waterjet (PWJ) and abrasive waterjet cleaning (AWJ) is shown in Figure 4. According to the plot for PWJ, surface roughness increases as pressure rises from 21 MPa to 41 MPa, then decreases drastically when pressure increases to 62 MPa. In overall, it was observed that for PWJ, the graph shows negative effect except for 41 MPa possibly due to at that point, the cleaning had achieved the threshold of cleaningThe surface roughness has been steadily reducing from 41 MPa to 62 MPa as a result of the waterjet's ability to smoothen the surface by eroding and deforming the peaks and valleys that were formed by the cleaning activity that came before it [13]. It was observed that in AWJ plot, pressure has a slight of positive impact on surface roughness. According to the graph, there are no different in surface roughness as pressure rises from 21 MPa to 41 MPa. However, the when pressure increases to 62 MPa the surface roughness increases slightly. In general, the AWJ results a positive trend as pressure increases. When the pressure is proportional to the size of the area being cleaned, the jet is able to remove paint from the same area multiple times after passing over it, but when an abrasive waterjet (AFR = 2 g/s) is used, which results in more penetration on the specimen and a higher level of surface roughness, the paint is removed from the same area more quickly. As pressure increases, the water particles' kinetic energy rises, leading to more materials being eroded [14][15]. High water supply pressure and water droplet impingement speed cause an increase in surface roughness. The capacity to erode materials may be improved by this increase in jet kinetic energy. This could lead to increased erosion and roughness on the material surface. [16]. For a low pressure of 21 MPa in PWJ and AWJ, Surface roughness shows better value. It is possible to attain greater Ra values with lower waterjet pressures as a result of the optimum contact that is maintained with the workpiece, the high kinetic energy of the abrasive particles and, the homogeneous mixing that occurs within the chamber [17].

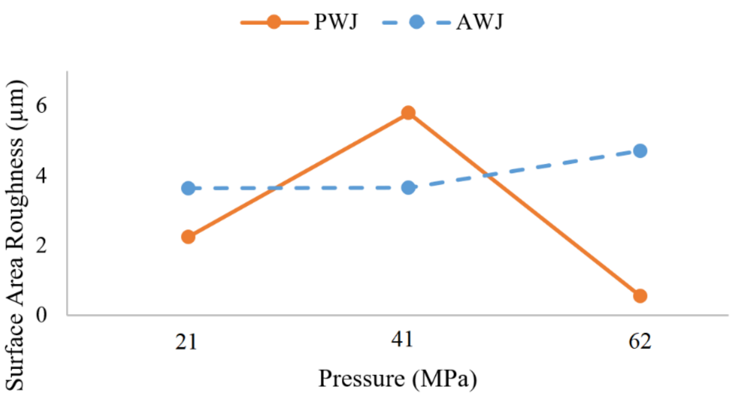

Figure 5. Effect of waterjet pressure on mean surface area roughness for plain and abrasive waterjet cleaning

The analysys of the effect of the number of passes on the mean surface area roughness is depicted in Figure 5 for both PWJ and AWJ. The graph for PWJ shows that the magnitude of the surface area roughness becomes substantially higher as the number of passes raises from one to two, but it gets significantly better again as the number of passes gets increased to three. In overall, it was observed that for PWJ, the graph shows negative effect except for 2 number of passes. It was observed that in AWJ plot, number of passes has a slight of negative impact on surface roughness. According to the graph, the surface roughness reduces from one pass to two passes as the number of passes increases from one to two. However, the when number of passes increases to 3 passes, the surface roughness increases slightly. In general, the AWJ results a negative trend as number of passes increases. Overall, the surface roughness for PWJ and AWJ is typically similar and varies between 3 µm to 6 µm. This result is in line with that of Huang et al., who found that R_a, which varies between 3 µm to 6 µm, remains mostly constant as the number of PWJ passes increases [8].

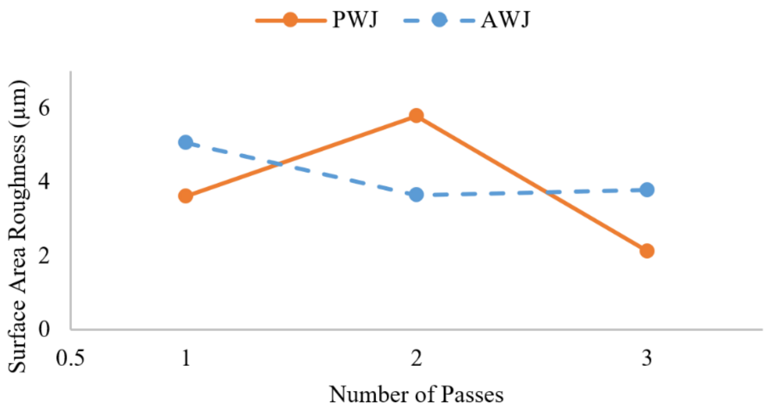

Figure 5. Effect of number of passes on mean surface area roughness for plain and abrasive waterjet cleaning

Figure 6 displays the analysis of the effect of overlap on surface area roughness in plain waterjet (PWJ) and abrasive waterjet cleaning (AWJ). According to the plot for PWJ, surface roughness increases as overlap rises from 25% to 50%, then decreases when overlap increases to 75%. In overall, it was observed that for PWJ, the graph shows no effect except for 50% overlap. It was observed that in AWJ plot, overlap has a slight of positive impact on surface roughness. High overlap indicates that low step-over distance between adjacent cleaning passes. Because it increases the volume of the target material impinged upon per unit area of the impinging waterjet and, as a result, more uniform material removal process, a low step over results in a decrease in R_a [17]. The results of this study, however, demonstrate the opposite impact, which may be caused by the presence of abrasive embedment in AWJ, which increases surface roughness. According to the graph of AWJ, the surface roughness decreases as overlap rises from 25% to 50%. However, the when overlap increases to 75%, the surface roughness increases slightly. For AWJ, surface roughness can reach an increment or decrement of maximum by 3 µm, while in PWJ, surface roughness can achieve an increment or decrement of 1 µm. This result is also consistent with the findings of Salinas et al., 2021, who came to the conclusion that an increase in surface roughness can go up to a maximum of 1 m when pressure and step-over distance are both raised, and it can go up to a maximum of 3 m when step-over distance is increased [18]. In overall, it is concluded that overlap result in little or no significant effect on surface roughness for PWJ and AWJ. This observation corresponds a similar trend with the results reported in the research conducted by Salinas et al., which came to the conclusion that the step-over distance parameter appears to have very little to no impact on surface roughness. As the pressure only varies at a traverse rate of 1.5 m/min, the surface roughness only slightly increases with increasing step-over distance [18]. Because the traverse rate was held at 90 mm/min throughout the entirety of the experiment, it is feasible that a reduction in the traverse rate could have a significant effect on the surface roughness.

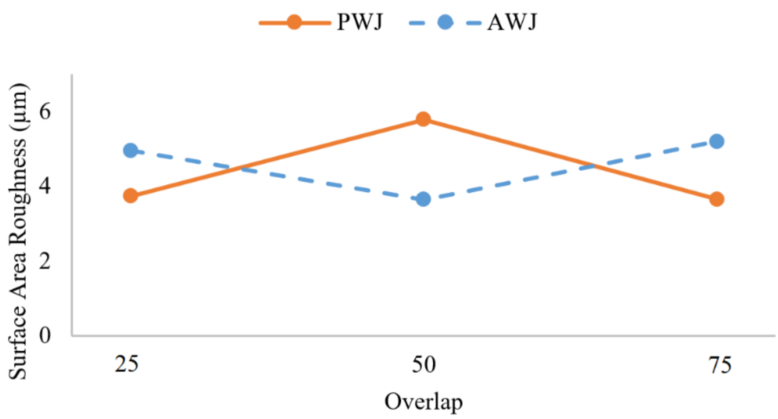

Figure 6. Effect of overlap on mean surface area roughness for plain and abrasive waterjet cleaning

Effect of waterjet parameter on Cleaning Efficiency

Figure 7 demonstrates the effect of pressure on cleaning efficiency for plain waterjet (PWJ) and abrasive waterjet cleaning (AWJ). It was observed that the cleaning efficiency of PWJ is extremely low as compared to AWJ. The cleaning efficiency of AWJ rises from 21 MPa to 41 MPa before remaining constant at 62 MPa. Abrasives accelerate more quickly at higher pressures, which increases the impact force from the waterjet on the paint and improves cleaning efficiency [19]. The cleaning efficiency is remain constant at 62 MPa is possibly due to at high pressure, more energy gain by the waterjet particle and abrasive to bombard the surface. More energy makes a particle move faster, which ultimately causes more collisions between particles. In addition, collision also can be present between the abrasives that first hit the coated surface and then rebound, and the incoming ones [19].

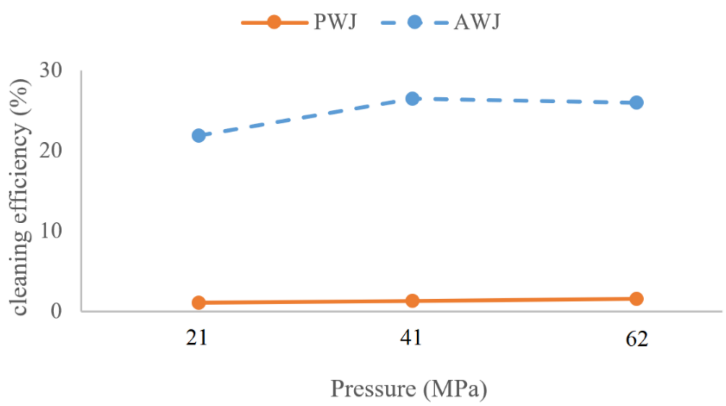

Figure 7. Effect of pressure on mean cleaning efficiency for plain and abrasive waterjet cleaning

Figure 8 demonstrates the effect of number of passes on cleaning efficiency for plain waterjet (PWJ) and abrasive waterjet cleaning (AWJ). It was observed that the cleaning efficiency of PWJ is extremely low as compared to AWJ. The cleaning efficiency of AWJ rises from 1 pass to 2 passes before slightly decreases at 3 passes. It has been observed that cleaning efficiency rises from 1 pass to 2 passes, presumably because there is no gap or coating tear in the 1 pass. At 2 passes, the gap is now created and widened to make cleaning generate more rapidly. Because of this, the most effective place to begin the coating removal using a high-pressure waterjet is at an area where the coating has been damaged and the gap formation requires constant cleaning if the coating is finished. [20]. Possibly, due to the formation of abrasive embedment on the cleaning surface after 3 cleaning passes on the same surface, the cleaning rather appears to remain constant at this point.

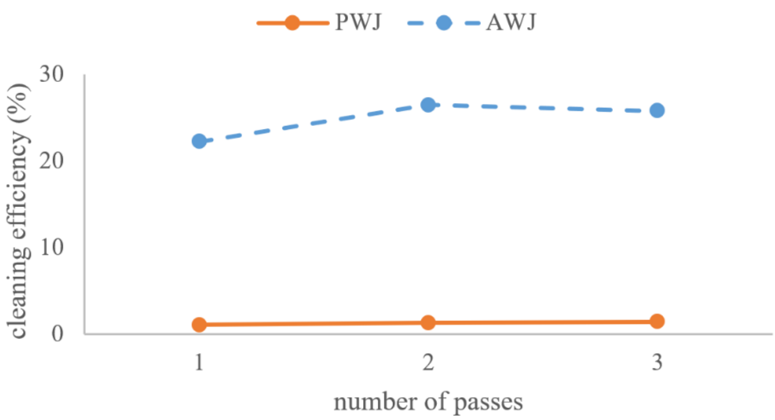

Figure 8. Effect of number of passes on mean cleaning efficiency for plain and abrasive waterjet cleaning

Figure 9 demonstrates the effect of overlap on cleaning efficiency for plain waterjet (PWJ) and abrasive waterjet cleaning (AWJ). It was observed that the cleaning efficiency of PWJ is extremely low as compared to AWJ. In general, the AWJ results a negative trend as overlap increases. Since low cleaning area corresponds to high overlap, it is reasonable to deduce that as the rate of overlap increases, cleaning efficiency decreases which is portray in the Figure 10. A reduced amount of material is eliminated when the overlap between one pass jet and the following becomes less [18]. In contrast, this research result in opposite findings to Salinas et al., due to that the cleaning efficiency focused more on area removal than volume removal.

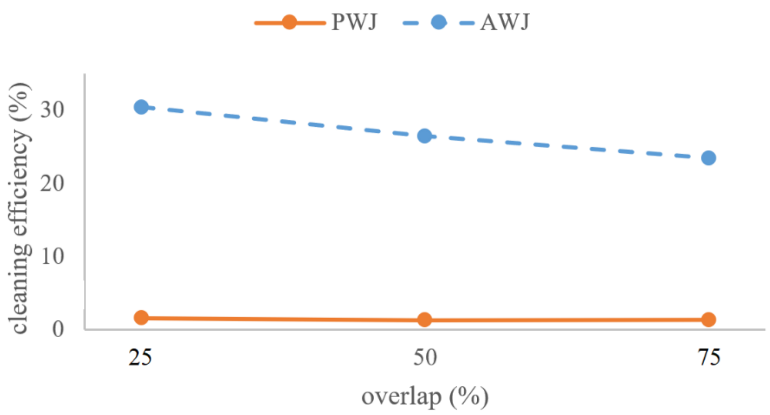

Figure 9. Effect of overlap on mean cleaning efficiency for plain and abrasive waterjet cleaning

Figure 10 shows the topography scans of samples after machining for run 26 for AWJ and PWJ paint removal processes and the sample topography before it was painted with their respective surface roughness. PWJ cleaning was proven to have a better surface finish in Figure 10 (b), where there were no evidence of bumps on the surface of the substrate, and the surface area roughness was near to the surface area roughness of the sample before it was painted at 0.939 µm. This situation arose due the the fact that the surface area roughness of the sample before it was painted remained unchanged as compared to the surface area roughness of the sample after it was painted. When compared to Figure 10 (c), the result demonstrated that it had a higher surface roughness than 4.6531 µm, and the imperfections are discernible on the surface of the substrate when AWJ cleaning is performed.

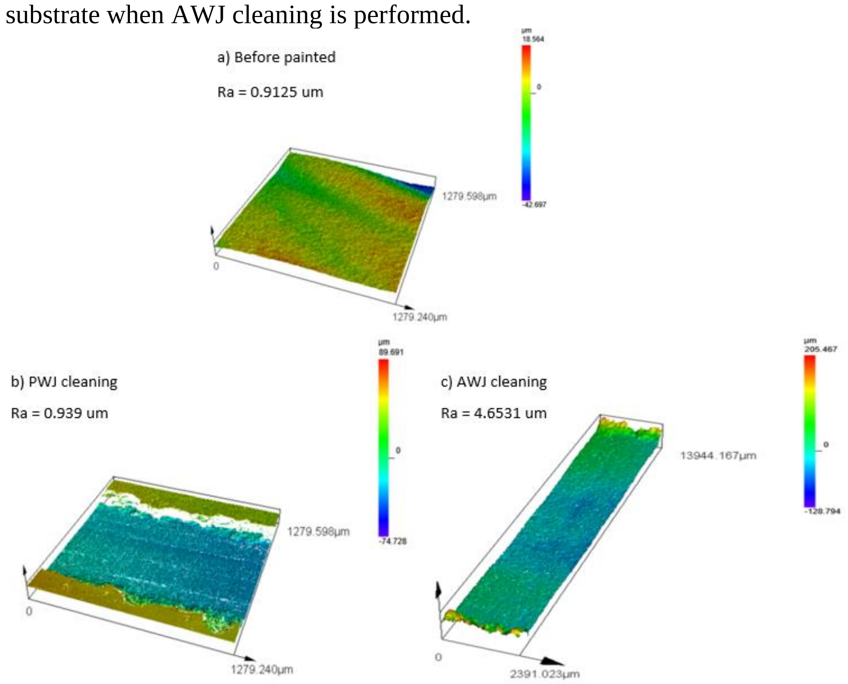

Figure 10. Surface Topography with surface roughness values of: (a) Sample before it was painted; (b) After PWJ cleaning (P = 62 MPa, n = 3, O% = 50%); (c) After AWJ cleaning (P = 62 MPa, n = 3, O% = 50%)

CONCLUSION

As a result of the fact that the cleaning settings have an effect on the WJ cleaning, it is vital to evaluate the waterjet cleaning parameters to assure a consistent high degree of cleanliness. Both the AWJ and PWJ cleaning produced uniform cleaning results, although the AWJ cleaning was more effective than the PWJ cleaning. The mean surface area roughness of the PWJ cleaning was lower as compared to the AWJ cleaning because there were no abrasive particles that were impacting the substate to break the material’s surface and raise the mean surface area roughness. A bigger overlap distance was obtained in AWJ paint removal, increasing the cleaning efficiency in AWJ paint removal, since AWJ cleaning produces a wider cleaning width than PWJ cleaning.

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