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Investigation on Optimum Waterjet Cleaning Parameters for Minimum Surface Impact during Paint Removal from Mild Steel

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ABSTRACT

In paint removal operations, one of the major areas of concentration is efficient cleaning, with the objective aiming to effectively remove paint while having as minimal impact as possible on the surface. Conventional cleaning methods, such as chemical and mechanical techniques, are widely utilized for paint removal despite their affordability, but they may face future prohibition due to environmental concerns. Waterjet cleaning is becoming more and more popular as a better cleaning technique that guarantees efficiency while also prioritising environmentally friendly. In the present investigation, a Box–Behnken design of the response surface methodology (RSM) was utilised in order to evaluate the influence that waterjet cleaning parameters had on painted mild steel. This was done so in order to determine the optimal waterjet cleaning parameters. The waterjet cleaning parameters that were selected were pressure, number of passes, and overlap rate. Output responses were considered to be the surface roughness, the material removal rate (MRR), and the cleaning rate. To predict surface roughness (R_a), cleaning efficiency, and material removal rate (MRR), workable empirical models have been created and an analysis of variance (ANOVA) was performed in order to determine the consistency of the results. The empirical models that were created for R_a, cleaning rate, and MRR all exhibit acceptable coefficients of determination and adequate correlations between the responses that were measured and the responses that were anticipated. For each response, a separate desirability function was used, which resulted in the generation of an entirely new set of optimal parameters. Both the anticipated and actual responses for optimised R_a, cleaning rate, and MRR are satisfactory, indicating that the model has a high degree of reliability. It has been demonstrated that the models are capable of accurately predicting the reactions of R_a, cleaning rate, and MRR in the context of the current investigation. The analysis identified that the optimal conditions for effective cleaning with minimal surface damage using abrasive waterjet cleaning are a pressure of 62 MPa, a single pass, and a 25% overlap rate**.** It is possible to construct a suitable selection of cleaning parameters that can be applied in practical works.

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1. Introduction

Over several decades, high-pressure waterjet technology has been explored and applied, and in that time, a primary goal of paint removal operations has been the efficient removal of paint while minimizing residual surface presence. Waterjet cleaning serves various purposes, encompassing activities such as blasting, chemical stripping, and sanding. However, these methods have inherent drawbacks that include product deformation, secondary contamination, and significant dangers to human health and the environment [1-3]. Waterjet cleaning uses high-pressure water to remove a variety of deposits or coatings off substrates, which can be made of metal or non-metal. Waterjet cleaning has the potential to address the constraints associated with traditional cleaning methods, notably by yielding a clean surface without the introduction of heat-related effects [3,4].

Response Surface Methodology (RSM) has now emerged as a popular method for optimizing parameters in various machining operations [5,6]. In AWJM, numerous researchers have investigated methods to enhance the process by optimizing its parameters using Response Surface Methodology (RSM). In a recent study, Tripathi *et al.,* [7] investigated the relationship between cutting speed and aperture and the MRR, SR, roundness, and cylindricity of the cut. Based on the optimal results of these academics, the recently developed Rao algorithm was proven to be more successful than the JAYA and TLBO algorithms when compared to each of those algorithms [7]. Using CCD of RSM and ANOVA, Doğankaya *et al.,* [8] investigated the impact of AWJM factors on UHMWPE plates. They discovered effective parameters and a trade-off between surface roughness and dimensional inaccuracy. When cutting X2 CrNiMo 17-12-2 austenitic stainless steel, Vora *et al.,* [9] utilised the Box-Behnken design of RSM with great success. As a result, they were able to achieve acceptable surface quality while simultaneously reducing their traverse speed and Sd. Using an L25 orthogonal array, Chaturvedi *et al.,* [10] optimised AWJM variables for the machining of Ti6Al4V alloy. They discovered that pressure was the most significant parameter determining the amount of time required for machining and the surface roughness. The research conducted by Thakur and Singh [11] optimised SR, MRR, and the delamination factor during AWJM by making use of input variables such as the percentage of MWCNT weight, the stand-off distance, the jet pressure, and the nozzle traverse rate. Using AWJM, Kumar *et al.,* [12] optimised the machining of an aluminium/ tungsten carbide composite. RSM was used to analyse both dependent and independent factors. The transverse speed was found to be the most important factor by ANOVA. In study by Fuse *et al.,* [13], a Box-Behnken design and a heat-transfer search (HTS) algorithm are used to evaluate the performance of abrasive water jet machining (AWJM) on Titanium alloys with the goal of obtaining maximum material removal rate (MRR) and minimal surface roughness (SR).

In this work, a Box-Behnken design is used to explore the cleaning efficiency and surface roughness in the context of abrasive waterjet (AWJ) and plain waterjet (PWJ) cleaning methods applied to mild steel material that has been covered with paint. The AWJ and PWJ cleaning methods were used to remove the paint from the mild steel material. The waterjet parameters of both AWJ and PWJ are meticulously analysed, and a comparative evaluation of their surface roughness, cleaning efficiency, and MRR is discussed. Waterjet parameters that are frequently employed in research investigations include standoff distance, traverse rate, and pressure. Some characteristics, including the number of passes and overlap rate, however, received minimal attention. Higher overlap rates during paint removal can lessen surface damage, according to laser cleaning research [14]. Therefore, the goal of this study is to investigate these novel parameters in order to determine the optimal values for cleaning rate, material removal rate (MRR), and surface roughness. This will allow for efficient paint removal with the least amount of substrate damage.

2. Methodology
2.1 Materials

In the present study, the experimental setup employed mild steel components with dimensions of 50 mm x 25 mm in surface area and a thickness of 5 mm as illustrated in Figure 1. The untreated substrate had an initial mean surface roughness (R_a) of about 1.2837 µm, while the painted substrate had an average R_a of around 0.8742 µm. Table 1 provides a comprehensive summary of the mechanical properties of the paint applied to the substrate, encompassing specific details on various parameters associated with the mechanical performance of the paint.

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

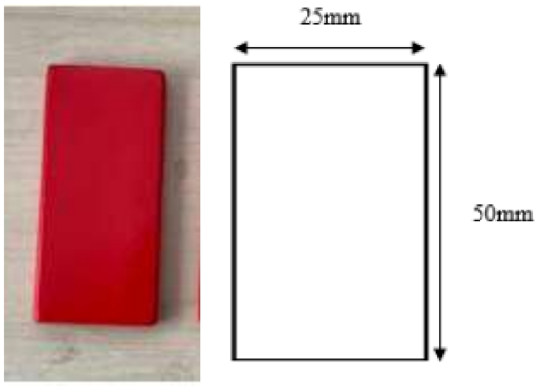


Fig. 1. Part shape and dimensions

2.2 Equipment

A commercial waterjet cutting machine with a computer numerical control (CNC) system that can produce pressures of up to 200 MPa was used in the experimental setting. The waterjet cutting machine is outfitted with a tungsten carbide nozzle that measures 0.76 mm in diameter and 76.2 mm in length. The specific commercial waterjet machine employed in this particular experiment is shown in Figure 2.

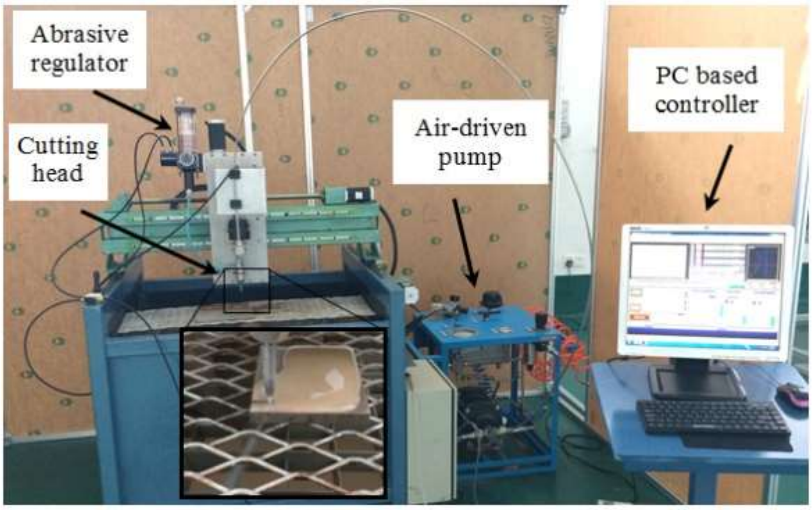


Fig. 2. Specific commercial waterjet machine

2.3 Experimental Design

There are several factors that affect the quality of the results when it comes to waterjet cleaning, therefore it is necessary to select only a limited set of parameters in order to assure the treatment's effectiveness. The waterjet cleaning parameters and their respective ranges are shown in Table 2. The standoff distance (SOD) was kept fixed at 50 mm since variations in the standoff distance have been shown to have a significant effect on surface roughness when combined with variations in overlap distance [15]. Moreover, the traverse speed was maintained constant at 90 mm/min in order to achieve uniform surface roughness. This choice was based on the observation that surface roughness (R_a) is positively correlated with traverse speed, indicating that traverse rate is the single most important factor influencing surface roughness [16]. Throughout all experimental trials, the orifice diameter and impact angle were maintained at constant values of 0.127 mm and 90 degrees, respectively. The sample was securely clamped onto the waterjet machine table, while the nozzle systematically traversed along the width of the sample. This traversal involved repeated overlapping impacts generated by the waterjet to effectively cleanse the designated area.To ensure efficient waterjet (WJ) cleaning, the cleaning width corresponding to the produced pressure levels, which were set at three distinct magnitudes, was used to calibrate the overlapping distance. For the purpose of this calibration, the standoff distance (SOD) was kept constant at 50 mm for both the pressure waterjet (PWJ) and abrasive waterjet (AWJ) cleaning techniques.

Table 2
Waterjet cleaning parameters and their respective levels

Waterjet Cleaning Parameters	Range		
	Low	Medium	High
Pressure, p (MPa)	21	41	62
Number of passes, n (pass)	1	2	3
Overlap, O (%)	25	50	75

According to the Box-Behnken experimental design, a total of 27 experimental runs were carried out for PWJ cleaning and 27 experimental runs for AWJ cleaning at a constant abrasive flow rate at 2 g/s in the present study. The layout of experiments and their corresponding surface roughness with cleaning efficiency are shown in Table 3 and Table 4. Design Expert, a software devoted to experiment design, was selected for the response surface methodology approach analysis of experimental data.

Table 3
Experimental runs and their results based on Box-Behnken experimental design for PWJ cleaning

Run	Waterjet cleaning parameters			Responses		
	Low	Medium	High	R_a (µm)	Cleaning efficiency (%)	MRR (g/min)
1	21	1	25	6.3302	1.05	0
2	21	1	50	4.8706	0.79	0.02835
3	21	1	75	4.897	0.29	0
4	21	2	25	4.6552	1.1	0.014175
5	21	2	50	2.2457	1.05	0.02835
6	21	2	75	2.654	1.15	0.014175
7	21	3	25	1.007	0.99	0.0945
8	21	3	50	2.4633	0.85	0.0945
9	21	3	75	2.5517	0.82	0
10	41	1	25	4.9135	1.2	0.02835
11	41	1	50	3.6243	1.05	0
12	41	1	75	3.088	0.92	0
13	41	2	25	3.7402	1.58	0
14	41	2	50	5.7912	1.28	0
15	41	2	75	3.6575	1.3	0.014175
16	41	3	25	1.425	1.31	0
17	41	3	50	2.136	1.4	0.00945
18	41	3	75	2.517	1.37	0
19	62	1	25	1.0427	1.39	0.02835
20	62	1	50	0.9832	1.37	0
21	62	1	75	1.2836	1.37	0.02835
22	62	2	25	1.2483	1.63	0.014175
23	62	2	50	0.549	1.54	0
24	62	2	75	0.8647	1.65	0
25	62	3	25	0.6196	1.5	0.0945
26	62	3	50	0.939	1.75	0
27	62	3	75	0.7586	1.61	0

The OLS5000 laser confocal microscope was used to quantify the surface area roughness in combination with the surface topography data. Cleaning efficiency is assessed through image processing, involving the segmentation of the machined area in images of the treated samples using MATLAB software. Images for each sample were captured with a consistent resolution, averaging 1000 × 500 pixels.

Table 4
Experimental runs and their results based on Box-Behnken experimental design for AWJ cleaning

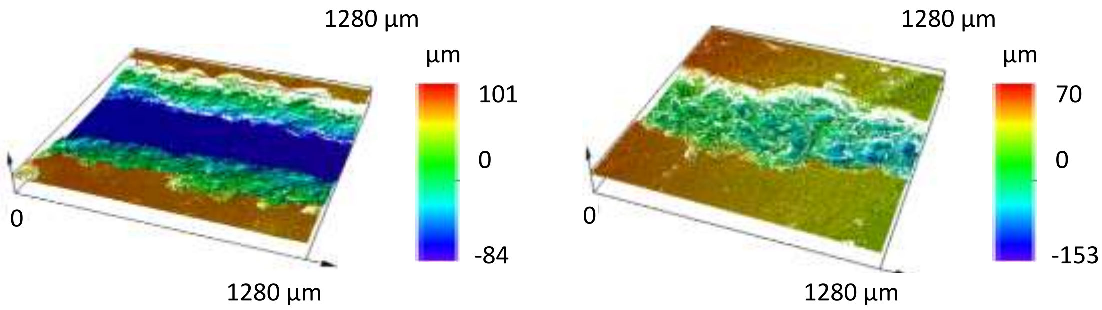
Run	Waterjet cleaning parameters			Responses		
	Low	Medium	High	R_a (µm)	Cleaning efficiency (%)	MRR (g/min)
1	21	1	25	2.3608	22.07	0.08505
2	21	1	50	2.8928	17.95	0.1134
3	21	1	75	3.1132	19.57	0.14175
4	21	2	25	3.0478	23.95	0.0567
5	21	2	50	3.6357	21.9	0.08505
6	21	2	75	3.384	17.16	0.1134
7	21	3	25	3.6892	20.99	0.02835
8	21	3	50	5.2162	27.19	0.02835
9	21	3	75	4.7312	17.09	0.04725
10	41	1	25	4.966	25.45	0.1701
11	41	1	50	5.0595	22.24	0.14175
12	41	1	75	5.3028	18.41	0.1134
13	41	2	25	4.9552	30.43	0.08505
14	41	2	50	3.649	26.47	0.0567
15	41	2	75	5.2042	23.44	0.06615
16	41	3	25	4.7123	28.04	0.08505
17	41	3	50	3.7863	25.79	0.0756
18	41	3	75	4.7442	20.08	0.2268
19	62	1	25	3.8391	28.6	0.19845
20	62	1	50	3.4241	24.87	0.14175
21	62	1	75	3.6776	22.6	0.14175
22	62	2	25	4.7428	29.57	0.14175
23	62	2	50	4.7142	25.98	0.1134
24	62	2	75	4.09	22.79	0.1134
25	62	3	25	3.4234	36.42	0.10395
26	62	3	50	4.6531	27.38	0.12285
27	62	3	75	4.499	26.73	0.10395

3. Results

3.1 Effect of Waterjet Cleaning Parameter on Surface Roughness

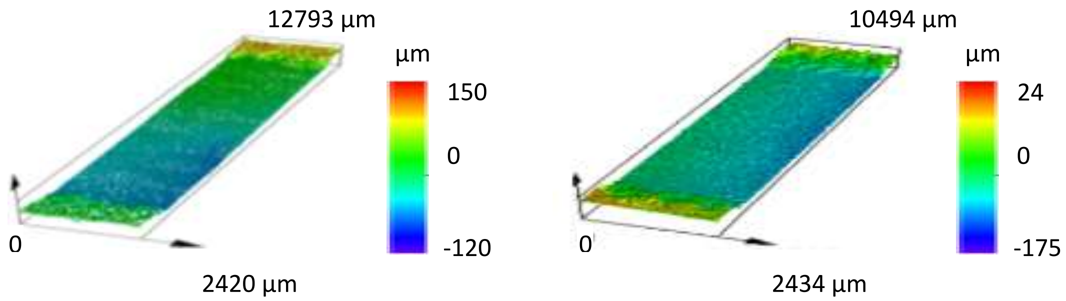
Table 3 and Table 4 present the experimental outcomes for roughness, cleaning efficiency, and MRR utilizing the Box-Behnken experimental design. It is important to highlight that the average original surface roughness stands at approximately 0.9125 µm. In the current investigation, post-cleaning treatment, the observed roughness values ranged from 0.549 (Run 23, Table 3) to 6.3302 µm (Run 1, Table 3) for PWJ and from 2.3608 (Run 1, Table 4) to 5.3028 µm (run 12, Table 4) for AWJ.

Figure 3 present the surface topography for paint removal using PWJ cleaning. In Figure 3(a) and Figure 3(b) shows high material removal with valley-to-peak ranges from 101 to 84 µm and 70 to 153 µm respectively. Notably, Figure 3(b) illustrates that the width of erosion on the surface is not consistent. Conversely, there is a constant erosion track with almost constant width for Figure 4(a). Moving on to Figure 4 present which present the surface topography for paint removal using AWJ cleaning, both figures an almost continuous erosion track. The material removal is markedly high with valley-to-peak almost the same 150 to 120 µm and 247 to 175 µm, respectively.



(a) (b)

Fig. 3. Surface topography for experiment (a) Run 23, Table 3 (R_a = 0.549 µm) and (b) Run 1, Table 3 (R_a = 6.3302 µm) for PWJ cleaning



(a) (b)

Fig. 4. Surface topography for experiment (a) Run 1, Table 4 (R_a = 2.3608 µm) and (b) Run 12, Table 4 (R_a = 5.3028 µm) for AWJ cleaning

Figure 5 and Figure 6 show the effect of three different cleaning parameter on the surface area roughness of the painted specimens for PWJ and AWJ cleaning respectively. In general, it is evident that an increasing in pressure results in lower surface roughness during the cleaning process with PWJ, whereas the opposite trend is observed in AWJ cleaning. This could be because when pressure rises, more kinetic energy is generated [17]. Because of the improved penetration through the painted and coated layers made possible by the higher pressure, a smoother surface is the resultant reduction in surface roughness. This observation is validate by the low surface roughness evident at a pressure of 62 MPa during PWJ cleaning, as depicted in Figure 3(a). During PWJ cleaning, it seems that a noticeable decrease in surface roughness occurs as the number of passes increases. Conversely, AWJ cleaning results in a marginal increase in surface roughness alongside a rise in the number of passes. It implies that the smoothening effect of the second and third passes on a particular surface assist in removing surface abnormalities by the final cleaning pass, similar to the effect shown in multi-pass cutting [15]. The overlap rate graph shows that for both cleaning methods, changes in the overlap distance have minimal impact on surface roughness.

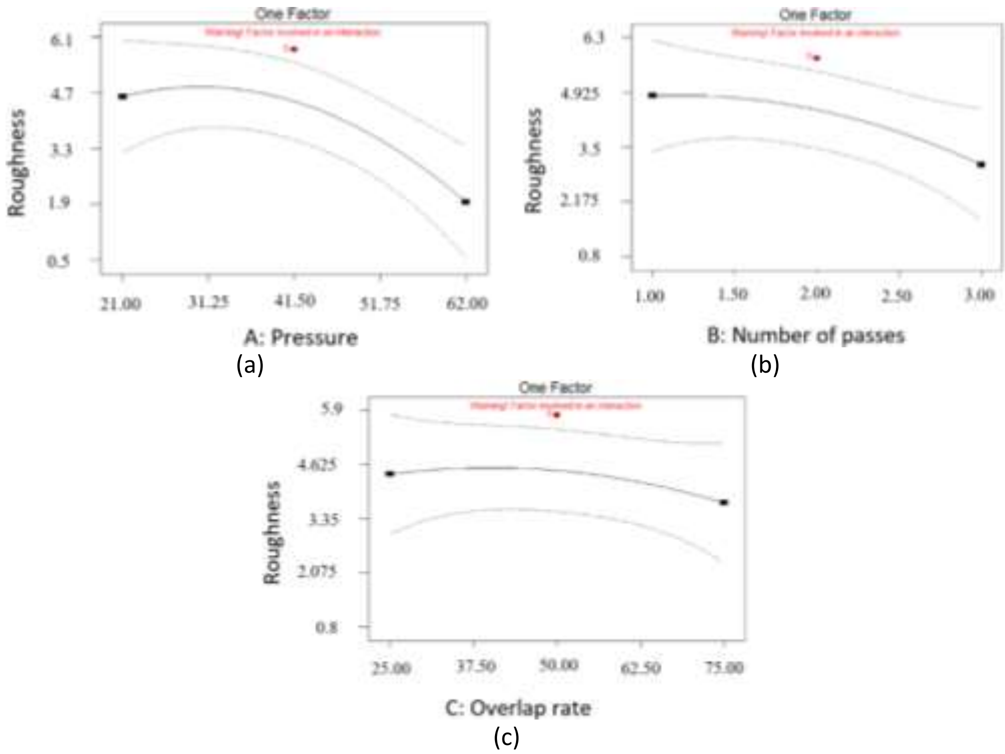


Fig. 5. Effects of PWJ cleaning of pressure, number of passes and overlap on surface roughness

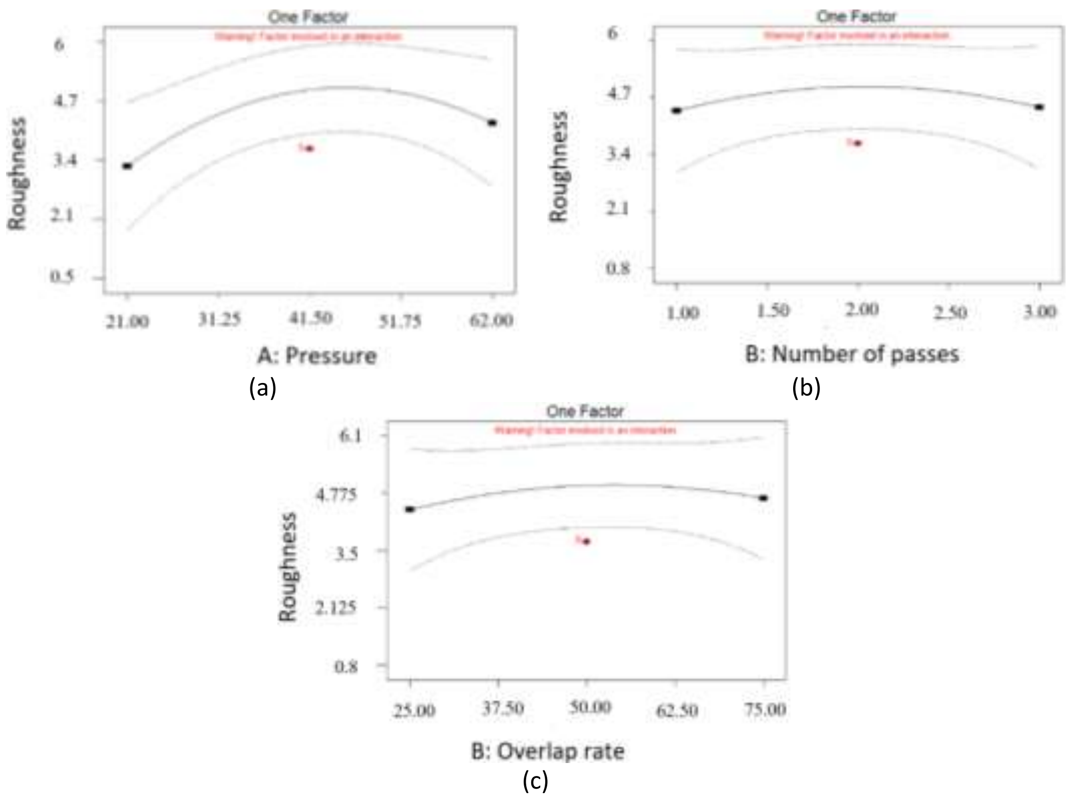


Fig. 6. Effects of AWJ cleaning of pressure, number of passes and overlap on surface roughness

3.2 Effect of Waterjet Cleaning Parameter on Cleaning Rate

In the present study, following the cleaning process, the recorded cleaning rate values varied between 0.29% (Run 3, Table 3) and 1.75% (Run 26, Table 3) for PWJ, and between 17.09% (Run 9, Table 4) and 30.43% (Run 13, Table 4) for AWJ.

Figure 7 displays the surface topography after PWJ cleaning, while Figure 8 illustrates the surface topography after AWJ cleaning, featuring both the minimum and maximum magnitudes of the cleaning rates. A notable erosion track is evident in both Figure 7 and Figure 8, except for Figure 7(a), where the possibly diminished effect may be attributed to the application of a lower number of passes in Figure 7(a) Run 3, Table 3), resulting in reduced cleaning and non-constant width of erosion track.

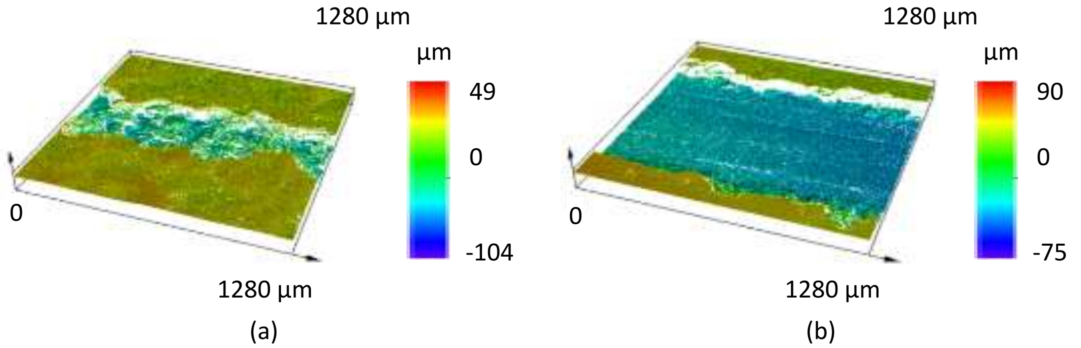


Fig. 7. Surface topography for experiment (a) Run 3, Table 3 (0.29 %) and (b) Run 26, Table 3 (1.75 %) for PWJ cleaning

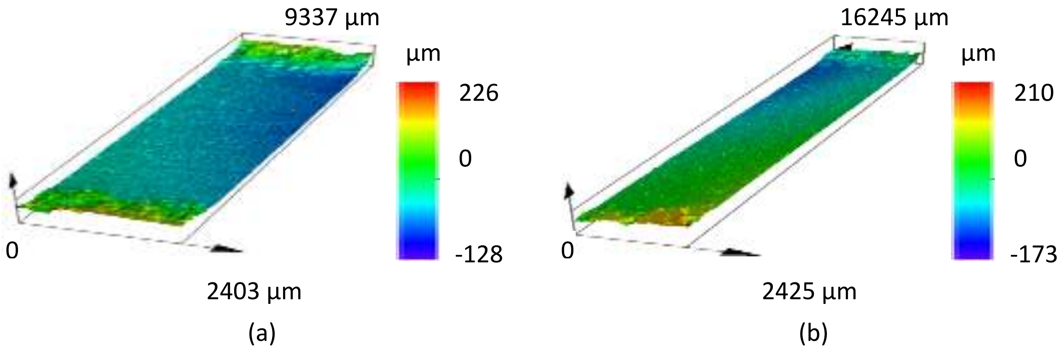


Fig. 8. Surface topography for experiment (a) Run 9, Table 4 (17.09 %) and (b) Run 13, Table 4 (30.43 %) for AWJ cleaning

Figure 9 and Figure 10 illustrate the impact of three distinct cleaning parameters on the cleaning rate of painted specimens for PWJ and AWJ cleaning, respectively. Figure 9 and Figure 10 distinctly demonstrate that AWJ cleaning yields a significantly higher cleaning rate compared to PWJ cleaning. This observation is substantiated by the cleaning rate values, indicating that the rate of cleaning is 30 times greater in AWJ than in PWJ cleaning. Furthermore, the surface topography depicted in Figure 5 and Figure 6 reinforces this finding, revealing an erosion track 10 times greater in AWJ cleaning than in PWJ cleaning. This could be attributed to the potentially elevated threshold cleaning capacity of AWJ paint removal in comparison to PWJ cleaning. When the threshold surpasses the cleaning capacity, the jet's penetration is too feeble to permeate the paint layer adequately [18,19].

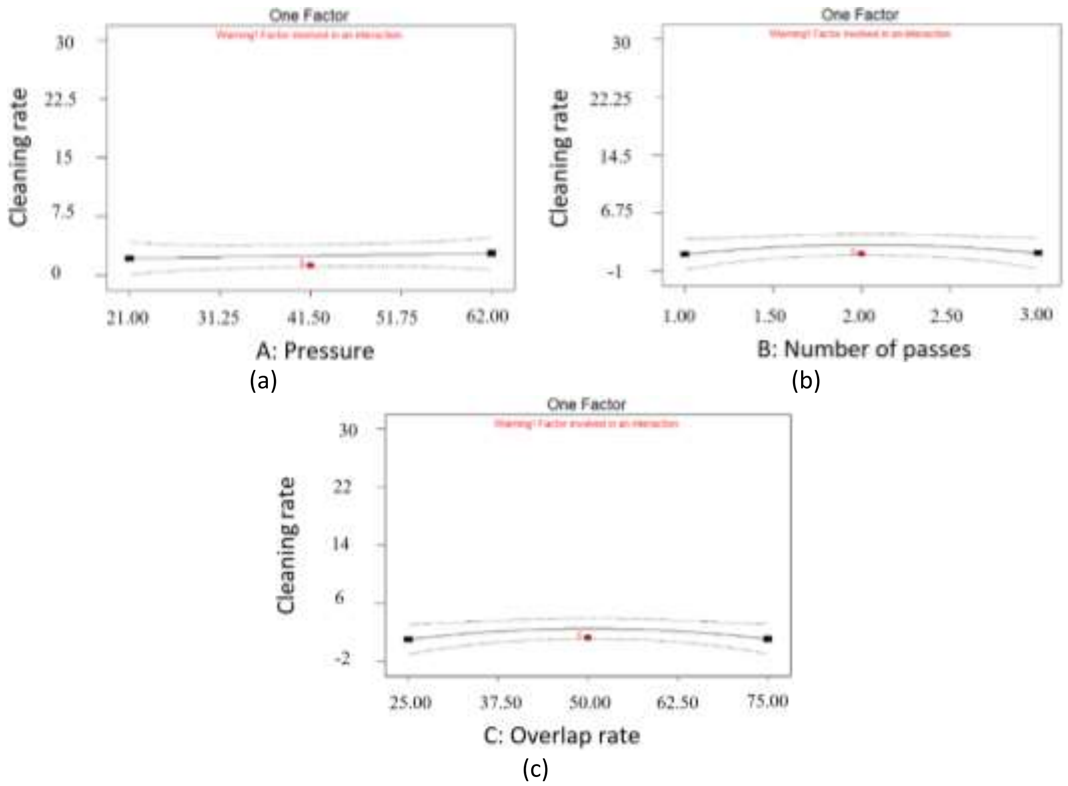


Fig. 9. Effects of PWJ cleaning of pressure, number of passes and overlap on cleaning rate

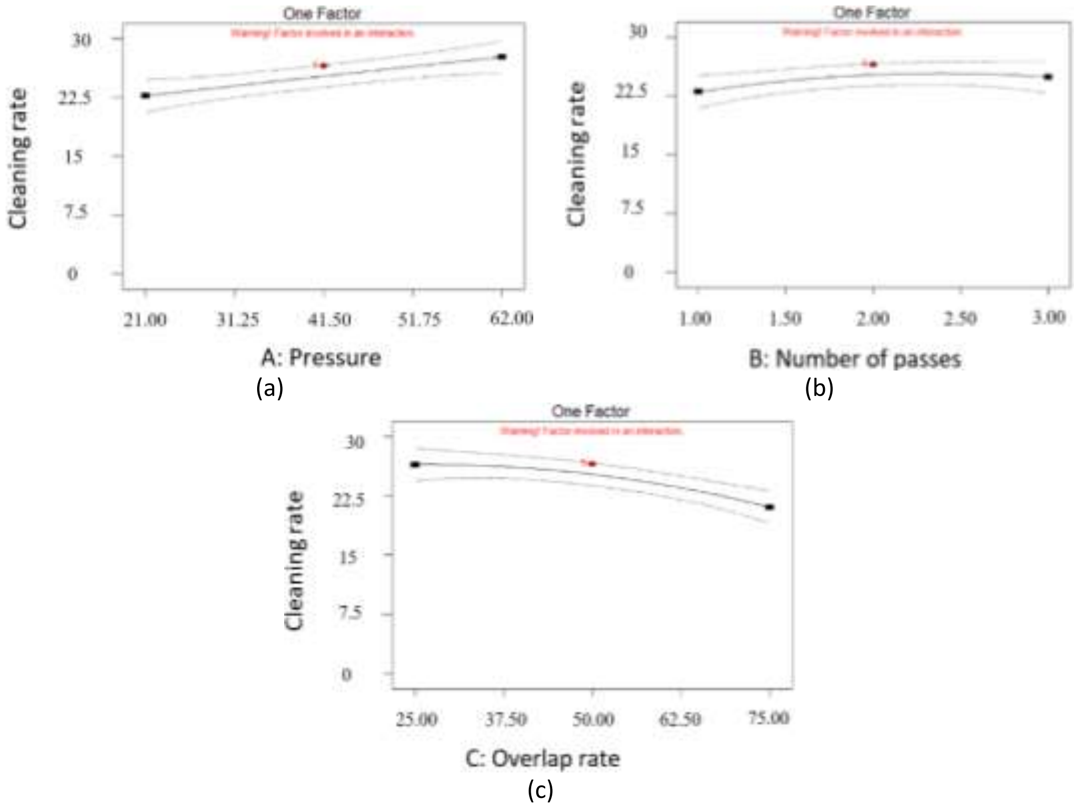


Fig. 10. Effects of AWJ cleaning of pressure, number of passes and overlap on cleaning rate

3.3 Effect of Waterjet Cleaning Parameter on MRR

In the current investigation, post-cleaning treatment, the observed MRR values ranged from 0 g/min (Run 1, Table 3) to 0.02835 g/min (run 21, Table 3) for PWJ and from 0.02835 g/min (Run 7, Table 4) to 0.19845 g/min (Run 20, Table 4) for AWJ.

Figure 11 shows the topography of the surface after PWJ cleaning, whereas Figure 12 shows the topography of the surface after AWJ cleaning, showing the lowest and highest values of Material Removal Rate (MRR). Erosion track is detected as more constant in Figure 11(b) and Figure 8 except for Figure 11(a). No significant MRR found in Figure 11(a) probably due to minimum cleaning parameter was applied which are 21 MPa pressure, 1 cleaning pass and 25% overlap rate. Material removal is more pronounced in AWJ cleaning compared to PWJ, as evidenced by higher valley-to-peak values in AWJ cleaning. Furthermore, the it is known that the use of abrasive results a higher MMR, thus more erosion occurs to the substrate compared to PWJ process [20].

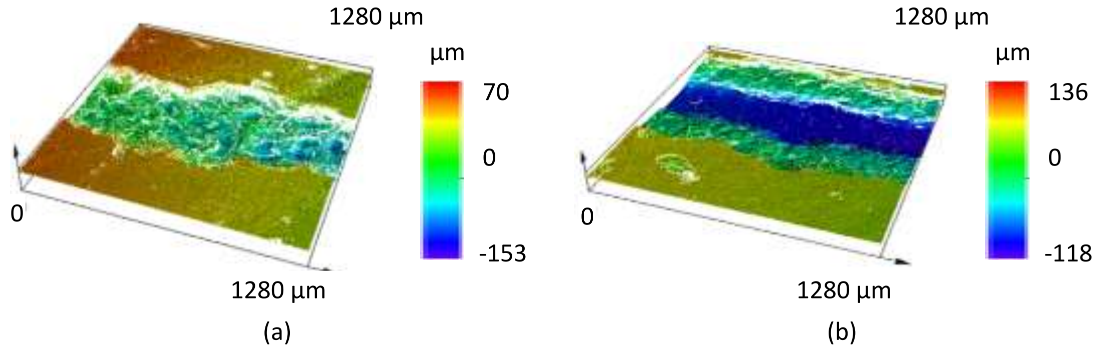


Fig. 11. Surface topography for experiment (a) Run 1, Table 3 (0 g/min) and (b) Run 26, Table 21 (0.02835 g/min) for PWJ cleaning

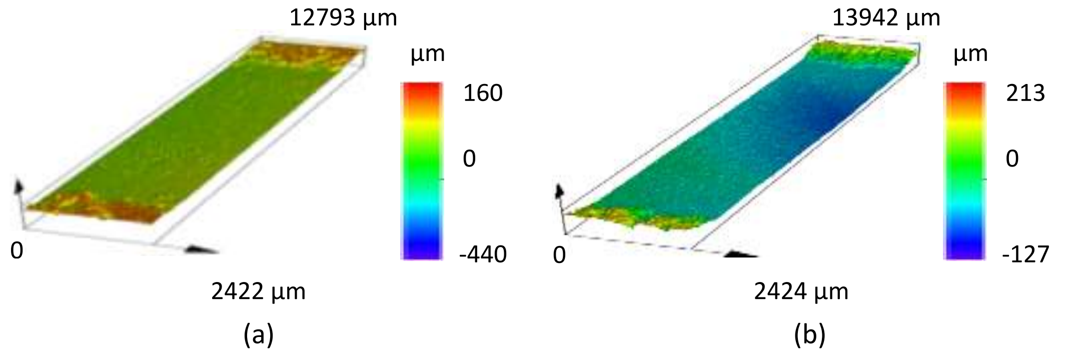
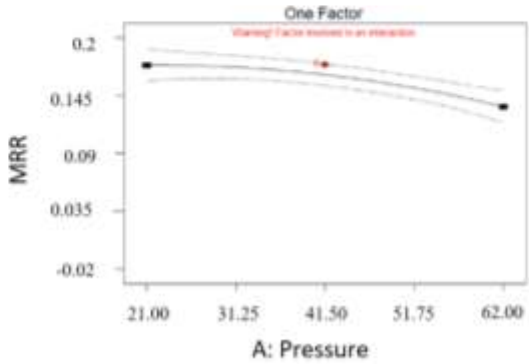
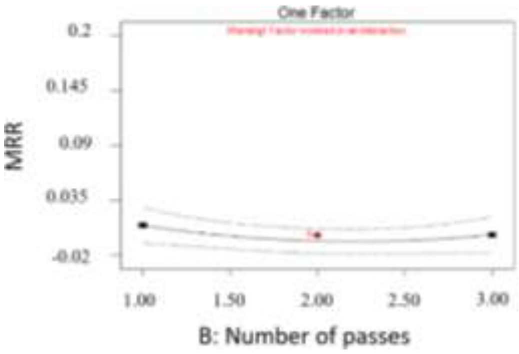


Fig. 12. Surface topography for experiment (a) Run 7, Table 4 (0.02835 g/min) and (b) Run 20, Table 4 (0.19845 g/min) for AWJ cleaning

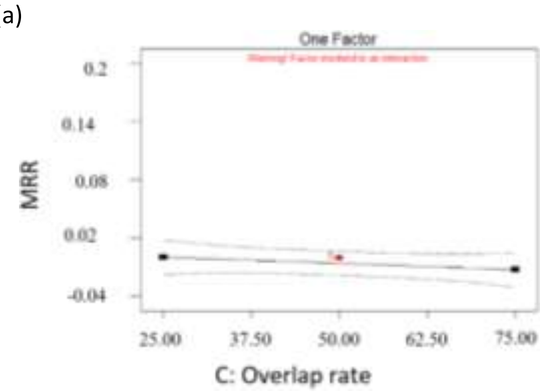
Figure 13 and Figure 14 delineate the influence of three distinct cleaning parameters on MRR of painted specimens in the scenarios of PWJ and AWJ cleaning, respectively. The comparison presented in Figure 13 and Figure 14 distinctly portrays that AWJ cleaning yields a significantly higher MRR when contrasted with PWJ cleaning. The heightened erosion observed in AWJ cleaning is attributed to the enhanced paint removal capabilities facilitated by the incorporation of abrasive particles in the waterjet. Additionally, elevated waterjet pressure may result in a high-impact force with a substantial normal component [21]. Notably, Figure 14 reveals an interesting observation that an increase in the number of passes reduces MRR in AWJ cleaning. This phenomenon may be explained by the additional embedment of abrasive particles during successive passes in AWJ cleaning, potentially generating more compressive stress on the surface, leading to a decrease in material removal with an increasing number of passes. This finding aligns with the results reported by Huang *et al.,* [22] who observed a decrease in embedded grit coverage or grit removal with an increasing number of PWJ passes.



(a)

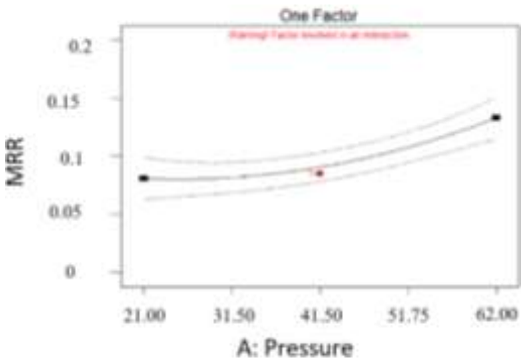


(b)

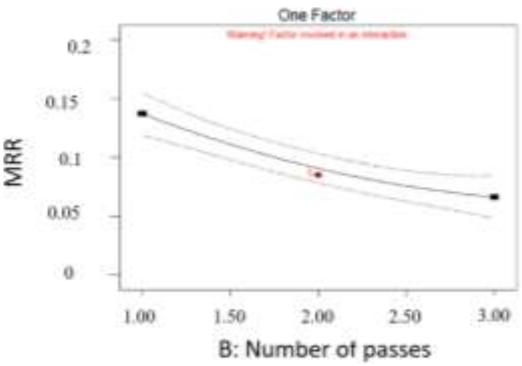


(c)

Fig. 13. Effects of PWJ cleaning of pressure, number of passes and overlap on MRR



(a)



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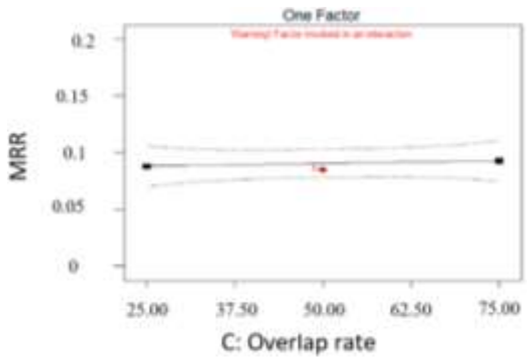

(c)

Fig. 14. Effects of AWJ cleaning of pressure, number of passes and overlap on MRR

3.4 Development of Empirical Equations

The empirical models for surface roughness, cleaning rate, and Material Removal Rate (MRR) were derived from the experimental datasets outlined in Table 3 and Table 4. These models were developed based on the outcomes of 27 experimental runs for each table, conducted following the principles of the Box-Behnken experimental design. Eq. (1), Eq. (2), and Eq. (3) articulate the second-order models that characterize the relationships between surface roughness, cleaning rate, and Material Removal Rate (MRR) with the parameters influencing waterjet cleaning.

$$Surface\ Roughness = +4.72 - 0.43 * A - 0.42 * B - 0.10 * C + 0.23 * D + 0.34 * A * B + 0.079 * A * C + 0.90 * A * D + 0.51 * B * C + 0.45 * B * D + 0.24 * C * D - 1.21 * A^2 - 0.51 * B^2 - 0.43 * C^2 \quad (1)$$

$$Cleaning\ rate = +13.87 + 1.39 * A + 0.52 * B - 1.33 * C + 11.34 * D - 0.63 * A * B - 2.500E-003 * A * C + 1.08 * A * D + 0.85 * B * C + 0.43 * B * D - 1.36 * C * D - 0.041 * A^2 - 1.24 * B^2 - 1.46 * C^2 \quad (2)$$

$$MRR = +0.043 + 9.745E-003 * A - 0.020 * B - 2.067E-003 * C + 0.048 * D - 3.544E-003 * A * B - 0.012 * A * C + 0.016 * A * D + 0.015 * B * C - 0.015 * B * D + 4.430E-003\ C * D + 0.016 * A^2 + 0.011 * B^2 - 2.953E-004 * C^2 \quad (3)$$

where A, B, C, and D are pressure, the number of passes, overlap rate, and waterjet type respectively.

Following that, an analysis of variance (ANOVA) was performed with the models and their parameters in order to determine the significance of the findings. The analysis of variance (ANOVA) is a statistical technique that is carried out primarily for the purpose of gaining knowledge about the influence of various design factors and for assessing the degree to which the outcome is sensitive to variations in the design parameters that affect the quality features. In addition, it is of the utmost importance to investigate any interactions that the analysis of the experimental design identifies as being significant. A higher F value shows that there is a significant change in the performance characteristic as a result of the alteration of the process parameter. This is indicated by the fact that the value of F has increased. In addition, the terms in the model are considered to have a significant effect on the answer if their p value is less than or equal to 0.05 [23]. The findings of the ANOVA are presented in Table 5, Table 6 and Table 7 for R_a, MRR and cleaning efficiency respectively. This investigation was carried out with a level of confidence of 95%. It was discovered that the individual p values for R_a, MRR and cleaning efficiency models have significance levels that are lower than 0.05. It demonstrates that both models should be considered significant.

Table 5
ANOVA for response Surface Quadratic Model for surface roughness

Source	Sum of Squares	dr	Mean Square	F Value	p-value Prob>F
Model	45.12	13	3.47	2.32	0.0438
A-Pressure	2.90	1	2.90	1.94	0.1791
B-Number of passes	2.76	1	2.76	1.85	0.1895
C-Overlap rate	0.17	1	0.17	0.11	0.7431
D-type	1.79	1	1.79	1.20	0.2863
AB	0.91	1	0.91	0.61	0.4442
AC	0.049	1	0.049	0.033	0.8576
AD	12.97	1	12.97	8.68	0.0080
BC	2.05	1	2.05	1.37	0.2548
BD	3.25	1	3.25	2.18	0.1556
CD	0.89	1	0.89	0.60	0.4491
A^2	12.24	1	12.24	8.19	0.0096
B^2	2.22	1	2.22	1.48	0.2375
C^2	1.55	1	1.55	1.04	0.3210
Residual	29.89	20	1.49		
Lack of Fit	29.89	12	2.49		
Pure Error	0.000	8	0.000		
Cor Total	75.00	33			
Std. Dev.	1.22	R-Squared	0.6015		
Mean	3.71	Adj. R-Squared	0.3425		
C.V.%	32.95	Pred R-Squared	-0.0784		
PRESS	80.88	Adeq Precision	5.589		

Table 6
ANOVA for response Surface Quadratic Model for MRR

Source	Sum of Squares	dr	Mean Square	F Value	p-value Prob>F
Model	0.10	13	7.849E-003	31.81	<0.0001
A-Pressure	1.520E-003	1	1.520E-003	6.16	0.0221
B-Number of passes	6.452E-003	1	6.452E-003	26.15	<0.0001
C-Overlap rate	6.837E-005	1	6.837E-005	0.28	0.6044
D-type	0.079	1	0.079	320.41	<0.0001
AB	1.005E-004	1	1.005E-004	0.41	0.5307
AC	1.231E-003	1	1.231E-003	4.99	0.0371
AD	4.221E-003	1	4.221E-003	17.11	0.0005
BC	1.887E-003	1	1.887E-003	7.65	0.0119
BD	3.773E-003	1	3.773E-003	15.29	0.0009
CD	3.140E-004	1	3.140E-004	1.27	0.2727
A^2	2.222E-003	1	2.222E-003	9.00	0.0071
B^2	1.005E-003	1	1.005E-003	4.07	0.0572
C^2	7.344E-007	1	7.344E-007	1.520E-003	0.9570
Residual	4.935E-003	20	2.468E-004		
Lack of Fit	4.935E-003	12	4.113E-004		
Pure Error	0.000	8	0.000		
Cor Total	0.11	33			
Std. Dev.	0.016	R-Squared	0.9539		
Mean	0.055	Adj. R-Squared	0.9239		
C.V.%	28.47	Pred R-Squared	0.8014		
PRESS	0.021	Adeq Precision	19.646		

Table 7
ANOVA for response Surface Quadratic Model for cleaning rate

Source	Sum of Squares	dr	Mean Square	F Value	p-value Prob>F
Model	4528.94	13	348.38	108.59	<0.0001
A-Pressure	31.00	1	31.00	9.66	0.0055
B-Number of passes	4.24	1	4.24	1.32	0.2637
C-Overlap rate	28.49	1	28.49	8.88	0.0074
D-type	4372.48	1	4371.48	1362.93	<0.0001
AB	3.14	1	3.14	0.98	0.3345
AC	5.000E-005	1	5.000E-005	1.559E-005	0.9969
AD	18.60	1	18.60	5.80	0.0258
BC	5.76	1	5.76	1.80	0.1952
BD	2.96	1	2.96	0.92	0.3484
CD	29.40	1	29.40	9.17	0.0067
A^2	0.014	1	0.014	4.466E-003	0.9474
B^2	12.95	1	12.95	4.04	0.0582
C^2	17.92	1	17.92	5.59	0.0283
Residual	64.16	20	3.21		
Lack of Fit	64.16	12	5.35		
Pure Error	0.000	8	0.000		
Cor Total	4593.10	33			
Std. Dev.	1.79	R-Squared	0.9860		
Mean	12.59	Adj. R-Squared	0.9770		
C.V.%	14.23	Pred R-Squared	0.9479		
PRESS	239.42	Adeq Precision	26.062		

Figure 15 demonstrates the interaction between pressure and overlap rate and its impact on Material Removal Rate (MRR). One observable finding is that increased pressure has a more noticeable effect on Material Removal Rate (MRR) at the lowest overlap rate of 25%. The Material Removal Rate (MRR) increases substantially at the minimum overlap rate as the pressure ascends from 21 MPa to 62 MPa. However, at the maximum overlap rate of 75%, the fluctuation in pressure is very slightly apparent. This implies that pressure and overlap rate have a significant interaction that affects the Material Removal Rate (MRR).

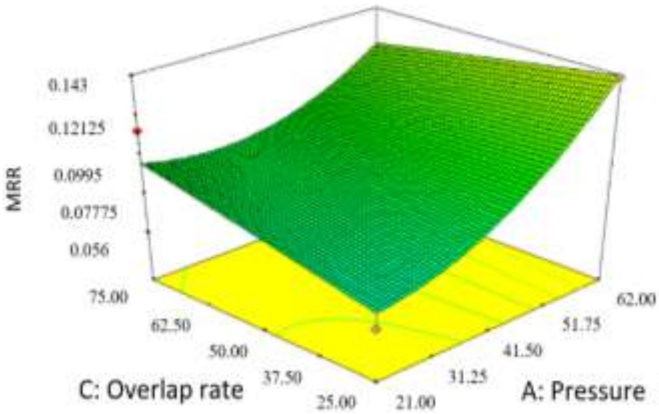

Fig. 15. Effects of interaction between pressure and overlap rate on MRR AWJ (AC interaction)

Figure 16 provides a visual representation of the correlation between the number of passes, overlap rate, and MRR When the overlap rate reaches its maximum of 75%, a slight fluctuation in the MRR can be seen for different numbers of passes. Conversely, MRR experiences a significant decline when transitioning from one to three passes at the minimum overlap rate of 25%. This implies a noteworthy interaction between the number of passes and overlap rate in this study, particularly evident at lower jet pass levels.

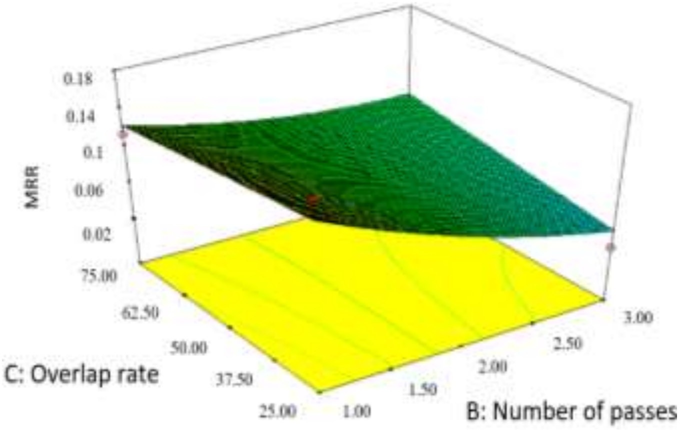

Fig. 16. Effects of interaction between number of passes and overlap rate on MRR AWJ (BC interaction)

In order to achieve optimal results, an analysis of response optimizations was carried out utilizing the generated models. The objective is to ascertain the optimal range of parameters within the scope of this study, aiming to achieve the maximum Material Removal Rate (MRR), the lowest surface roughness, and the highest cleaning rate concurrently. In order to optimise response processes, the Design Expert software's desirability function technique was utilised to get optimal parameter. Table 5 shows the optimum parameter using Box-Behnken design. The optimum parameter was found to be at pressure of 62 MPa, number of passes is 1, overlap rate 25% using abrasive waterjet cleaning as shown in Table 8.

Table 8
Optimization

No	P	n	O	Type	Ra	MRR	Cleaning rate	Desirability	
1	62.00	1.00	25.00	abrasive	3.19805	0.207979	28.168	0.794	Selected

4. Conclusions

Drawing conclusions from the application of the Box-Behnken experimental design methodology in the context of waterjet cleaning parameters, insights into the effects on the cleaning process of mild steel using both PWJ and AWJ can be established as follows

i. Surface roughness values for PWJ and AWJ were found to be between 0.549 and 6.3302 µm and 2.3608 and 5.3028 µm, respectively. When using PWJ, there is often a positive correlation between increasing waterjet pressure and decreased surface roughness; however, when using AWJ, there is a negative correlation.
ii. During the cleaning process, the recorded cleaning rate values for PWJ varied from 0.29% to 1.75%, while AWJ had values ranging from 17.09% to 30.43%. In contrast to PWJ cleaning efficiency, AWJ cleaning exhibits a wider cleaning width, which increases paint removal efficiency.

iii. For PWJ, the recorded Material Removal Rate (MRR) values ranged from 0 g/min to 0.02835 g/min, and for AWJ, they varied from 0.02835 g/min to 0.19845 g/min. In comparison to the PWJ method, the use of abrasives results in a higher MRR and more substrate degradation.
iv. This research aimed to achieve the highest Material Removal Rate (MRR), minimize surface roughness, and maximize cleaning rate. The optimal parameters were determined to be a pressure of 62 MPa, a single pass, and an overlap rate of 25% in the context of abrasive waterjet cleaning.

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