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Experimental Study on Abrasive Waterjet Polishing of Hydraulic Turbine Blades

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Abstract. In this paper, an experimental investigation is implemented on the abrasive waterjet polishing technique to evaluate its capability in polishing of surfaces and edges of hydraulic turbine blades. For this, the properties of this method are studied and the main parameters affecting its performance are determined. Then, an experimental test-rig is designed, manufactured and tested to be used in this study. This test-rig can be used to polish linear and planar areas on the surface of the desired workpieces. Considering the number of parameters and their levels, the Taguchi method is used to design the preliminary experiments. All experiments are then implemented according to the Taguchi L_{18} orthogonal array. The signal-to-noise ratios obtained from the results of these experiments are used to determine the importance of the controlled polishing parameters on the final quality of the polished surface. The evaluations on these ratios reveal that the nozzle angle and the nozzle diameter have the most important impact on the results. The outcomes of these experiments can be used as a basis to design a more precise set of experiments in which the optimal values of each parameter can be estimated.

1. Introduction

Hydraulic turbines are used to convert the potential energy of the water into kinetic energy to turn an electric generator and produce electricity. One of the factors which affect the efficiency of these turbines is the friction between the water and the surface of the blades. Thus, it is highly desirable to decrease the amount of the friction loss. Friction depends on the quality of the finished surface which is identified as the deviation of the real profile of a machined surface from its nominal designed shape. This variance is known as the waviness and roughness of the surface [1]. To increase the efficiency of the turbines, roughness and waviness of the surfaces should be improved. Consequently, in a hydraulic turbine manufacturing industry, after initial machining processes, some supplementary procedures such as grinding and polishing are required.

So far, different methods such as abrasive sanding belts/discs are used to perform this step. However, polishing narrow areas requires a particular technique which can access these hard-to-reach areas and appropriately polish them. To do this, a non-conventional technique such as abrasive waterjet (AWJ) machining can be used. Indeed, it can machine almost all types of materials including metals, nonmetals, composites and nanomaterials [2].

Modifying an AWJ system to perform a more delicate process such as polishing is a novel technique and the current information around this particular application of AWJ is limited.

This technique is also known as abrasive waterjet polishing (AWJP) and was developed at Delft University of Technology in 1998. In this method, a medium pressure pump delivers pure/abrasive water to a nozzle to produce the abrasive jet [3].

In AWJP, two types of material removal take place: brittle and ductile removal. In the former, the kinetic energy of leads to material removal while the latter happens by shearing action between abrasives and the surface [3, 4]. In general, several factors affect the performance of this machining system including: abrasive material type/size, velocity of jet, abrasive feeding rate, stand-off-distance (SOD), and the angle between the nozzle axis and the tangential plane at the polishing spot [3]. Compared to traditional polishing methods, using AWJP provides several advantages such as no contact between the polishing tool and the workpiece, no change to the physical and mechanical properties of the surface, no thermal effect on the surface, polishing hard-to-reach areas, and high machining versatility [2, 3, 5, 6]. In AWJP, depending on the hardness of the workpiece usually the slurry goes across the nozzle with a pressure up to 150 bar [3, 4, 7]. For instance, Zhu et al, [4] used waterjet with a pressure of 20-150 bar to polish hard materials such as silicate glass, alumina ceramic and silicon nitride ceramic. In this technique, the inner diameter of the nozzle varies from 0.3 to 4 mm and the SOD is in the range of $10 - 100$ mm [3, 4, 8].

In addition, different types of abrasive grains like cerium oxide, silicon carbide, aluminum oxide, and boron carbide are used in this process [3, 7, 9, 10]. The size of these abrasive grains is selected based on the material of the workpiece and the required quality for the surface. Indeed, larger abrasive grains increase the material removal rate while using smaller ones results in a very smooth surface but increases the polishing time [9]. The effect of nozzle angle on the AWJP process is also investigated by Li et al. [3]. They simulated the material removal process for two different nozzle inclination angles. Their investigation showed that, the width of the polishing zone increases when the nozzle angle is changed from normal to oblique angle. Consequently, in AWJP, the nozzle is usually tilted [3, 8, 10].

Considering all parameters affecting the performance of the AWJP process, some researchers have presented general analyses on the nature of this system and tried to obtain the best set of parameters for a particular application. For example Chen and Wang [11] investigated the effect of the AWJP on the roughness of the surfaces of two different materials. They used the Taguchi method to design their experiments. As a result of these tests, they found the impact of each parameter on the quality of the surface and optimized these parameters. In their experiments, they used Al_2O_3, CeO_2 and SiC grains as abrasive and also 40CrMnMo7 steel and BK7 glass as materials for the workpiece. Their results revealed that the nozzle diameter has the most and the SOD has the least important impact on the roughness (R_a) of the surface. Luc et al. [12] performed a similar study on the AWJP of Zr-based balk metallic glass and tried to optimize the polishing parameters using Taguchi method. They also developed another test-rig to do a similar investigation on the air-driven waterjet polishing of N-BK7 workpiece [13]. Again, using Taguchi method they found the best polishing parameters for this particular application.

In this study, to evaluate the capability of this method in polishing of hard-to-reach areas of the hydraulic turbines, an experimental study is implemented. For this, the main parameters affecting the performance of the process are first determined. Next, an experimental test-rig is designed and built to do the experiments. Then, by developing a proper DOE, the tests are implemented on workpieces with properties similar to those of the hydraulic turbines. Through this study, the effect of the polishing parameters on the quality of the surface (its roughness) is investigated. The results of these tests are then used to find the parameters which have the highest impact on the surface quality. The outcomes of this study will be used to implement further experiments and optimize the main polishing parameters which will be ultimately considered in the AWJP of the real surfaces of the hydraulic turbines in the near future.

Table 1. Parameters and their ranges considered in the design of the test-rig.

Parameters	Required range	units
Water pressure	10 - 150	bar
Water flow rate	0.5 - 40	l/min
Abrasive feeding rate	50 - 1500	gr/min
Nozzle diameter	0.5 - 2.5	mm
Nozzle angle	15 - 90	deg
Nozzle SOD	0 - 100	mm
Traversing speed	0 - 5	mm/s
Workpiece dimensions (L×W max)	250 × 250	mm
Polishing zone dimensions (L×W×H)	1000 × 800 × 900	mm

2. Designing and dimensioning the test-rig

The test-rig should be designed in such way that all ranges of the parameters which are considered in the experiments are properly covered. They can be categorized as polishing parameters and design parameters. Based on the literature and the case study, the range of the main parameters considered in the design of the test-rig are selected as listed in Table 1.

The abrasive waterjet production cycle can then be designed. Generally, two methods are used to mix water and abrasives. In the first, the water and abrasives are mixed in a tank and then the mixture is the pumped toward the nozzle. In the second type, pure water is pumped toward a nozzle head where it is mixed with the abrasives either before or after the orifice. If the abrasives are added to the water before the orifice, then a venturi is used to suck the mixture of water and abrasive which was prepared in a separate tank. Otherwise, an ejector is used to suck the dry abrasives and add it to the jet (similar to abrasive waterjet cutting method). Among these systems, the last one (using an ejector) which is simpler and cheaper is considered in the design of the test-rig. After consultation with Waterjet Technologies AG [14, 15] the cycle of this system is designed as illustrated in Fig. 1.

In this system, a diaphragm pump is used to produce the desired water flow and head. The selected pump can provide a pressure up to 170 bar and a flow rate up to 50 l/min. A frequency converter is used to adjust the water flow rate by controlling the speed of the pump. In addition, a pressure valve is used to manually adjust the desired pressure (and so the speed of the waterjet). This valve returns the surplus fluid back to the mixing tank. Next, considering this cycle and the required characteristics all other parts of the test-rig are designed. This test-rig is mainly composed of three units:

1. **Water tank**: includes the tank and the chassis. The capacity of the storage tank is 360 L and thus, the system can continuously operate at least for seven minute if the maximum flow rate is needed. The chassis is used to place the tank in the proper elevation to maintain the $NPSH_r$ (required Net Positive Suction Head);
2. **Pump unit**: comprised of the pump, electric motor, frequency converter, pressure valve, safety valve, and gauges. This unit provides the desired pressure and flow rate;
3. **Polishing unit**: includes a chassis, catcher tank, bench, tilting unit, abrasive hopper, nozzle head, septic tank, and transparent shields. In this unit, the tilting unit places the nozzle head in the desired location and orientation with respect to a workpiece (which is fixed to the bench inside the catcher tank) to perform the polishing process. The abrasive material is added to the system using gravity and the suction of the ejector which is connected to the abrasive hopper via a flexible hose.

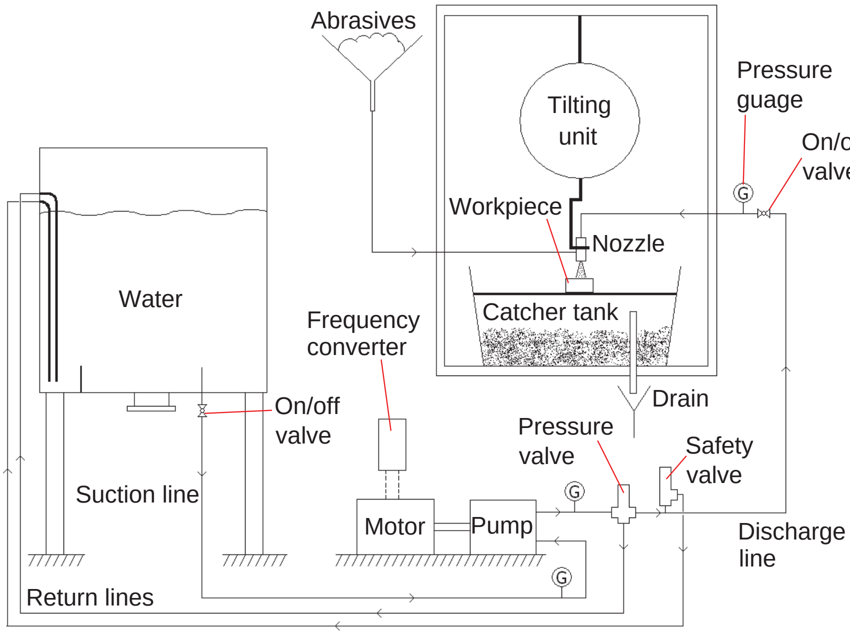

Figure 1. Diagram of the waterjet production cycle.

3. Manufacturing the test-rig

After designing all structural components and selecting all the required equipment, they are assembled in the site. The final installation of the test-rig designed based on consultation with Waterjet Technologies AG is shown in Fig. 2 (left). As shown in this figure, dry abrasives are added to the waterjet inside the ejector. The abrasive hopper was installed on the top of the polishing unit to compensate the problem of weak suction of the ejector at low water pressure. In the tilting unit developed for this test-rig, one of the two axes of the X-Y table used for planar movement of the nozzle head is actuated using a worm gear DC motor and the other axis is operated manually. The nozzle head is attached to a vertical pipe though a particular tool designed to place this nozzle in the desired position and orientation so that the SOD and nozzle angle can be adjusted.

After evaluating the performance of the modified test-rig via several tries, it was ready to perform the initial tests on the performance of the AWJP process. This test-rig can be used to perform linear and planar polishing experiments, but with the current tilting unit only linear polishing can be done automatically.

4. Design of the experiments (DOE)

The main objective of these experiments is to investigate the effect of polishing parameters on the AWJP process (i.e., improvement in the roughness of the polished surface). For this, seven polishing parameters are determined to be evaluated in polishing of straight lines on flat surfaces. They are:

1. Nozzle diameter (D)
2. Abrasive type (A)
3. Abrasive feeding rate (W)
4. Nozzle angle (N)
5. Stand-off-distance (S)
6. Water pressure (P)
7. Number of passes (T)

Figure 2. (left) Final installation of the test-rig; (right) nozzle head and the ejector installed on its tip.

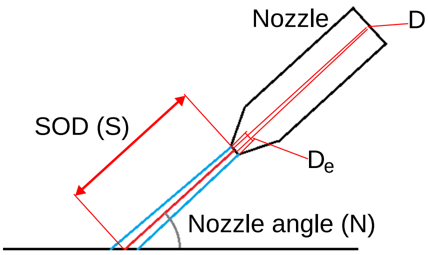

Figure 3. Definition of dimensional polishing parameters.

Table 2. Definition of the levels of the controlled polishing parameters.

Parameters	units	Levels		
		1	2	3
D	mm	1.5	2	—
A	—	Garnet #120	Glass beads BT10	Corundum F100
W	gr/min	300	800	1200
N	deg	30	60	90
S	mm	20	50	70
P	bar	60	100	140
T	pass	2	4	6

The definition of nozzle angle (N) and stand-off-distance (S) are presented in Fig. 3. In these tests, the diameter of the ejector throat D_e is 4.5 mm and the traversing speed of the nozzle along the polishing line, v_t, is fixed to 1 mm/s. To investigate the relationships between the polishing parameters and the outputs (to see if they can be described by linear functions or not), for each parameter, three values (here called as levels) are chosen except for the nozzle (orifice) diameter (D) where only two sizes were available. All the parameters and their levels to be used in the DOE are listed in Table 2. As can be seen in this table, three types of abrasives are considered for these experiments. The size of all these abrasive particles are around 100 - 150

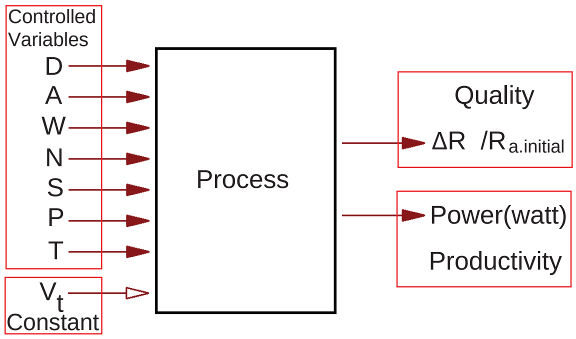

Figure 4. Diagram of the DOE with controlled input variables, constant input and outputs.

Table 3. L_{18} orthogonal array of experiments (OAE) presented in Taguchi method

Test no.	Parameters							$\Delta R_a/R_{a.initial}$			S/N Ratio (Mean)
	D	A	W	N	S	P	T	Trail 1	Trail 2	Trail 3	
1	1	1	1	1	1	1	1	0.189	0.084	0.315	-7.624
2	1	1	2	2	2	2	2	0.345	0.547	0.436	4.523
3	1	1	3	3	3	3	3	0.417	0.370	0.372	5.058
4	1	2	1	1	2	2	3	-0.135	-0.202	0.216	-4.44
5	1	2	2	2	3	3	1	0.037	-0.021	0.016	-22.159
6	1	2	3	3	1	1	2	0.416	0.492	0.433	5.256
7	1	3	1	2	1	3	3	0.494	0.488	0.436	6.001
8	1	3	2	3	2	1	1	0.416	0.568	0.443	5.291
9	1	3	3	1	3	2	2	0.301	0.165	0.357	-0.306
10	2	1	1	3	3	2	1	0.165	0.209	0.158	-1.487
11	2	1	2	1	1	3	2	-0.279	-0.247	-0.210	1.321
12	2	1	3	2	2	1	3	0.287	0.348	0.476	3.201
13	2	2	1	2	3	1	2	-0.162	-0.043	-0.211	-8.252
14	2	2	2	3	1	2	3	0.456	0.286	0.271	1.762
15	2	2	3	1	2	3	1	0.017	-0.143	-0.014	-19.725
16	2	3	1	3	2	3	2	0.348	0.263	0.129	-3.258
17	2	3	2	1	3	1	3	-0.024	-0.384	-0.274	-14.476
18	2	3	3	2	1	2	1	0.346	0.437	0.443	5.105

μm. Also Garnet and Corundum abrasives have blocky & sharp shapes but Glass beads have a round shape.

The diagram of the DOE including the controlled input variables, input constant, and desired outputs is illustrated in Fig. 4. With seven parameters and their associated levels (Table 2), if all possible combinations as full-factorial experiments (FFE) are chosen then, in total, $2 \times 3^6 = 1458$ tests have to be done. Obviously, performing this number of experiments is impractical. Therefore, to decrease the number of these preliminary tests to a reasonable value, the L_{18} orthogonal array of experiments (OAE) presented in Taguchi method is used [16]. Consequently, the number of the experiments is reduced to 18. However, these tests are not enough to reveal the effect of each parameter on the results. Instead, Taguchi method shows the significance of the parameters on the results. Therefore, this method is suitable for preliminary tests where the key parameters are determined. Then, the number of the parameters to be examined in further experiments can be reduced and consequently a more comprehensive DOE

Table 4. Properties of the workpieces used in experiments.

Property	Description
Material [17]	ASTM A743 CA6NM
Yield strengh [17]	100 ksi
Surface hardness [17]	Brinell hardness (HBW) 268
Dimension	5" × 5"
Surface machining method	Sawing (with trace of parallel scallops on the surface)

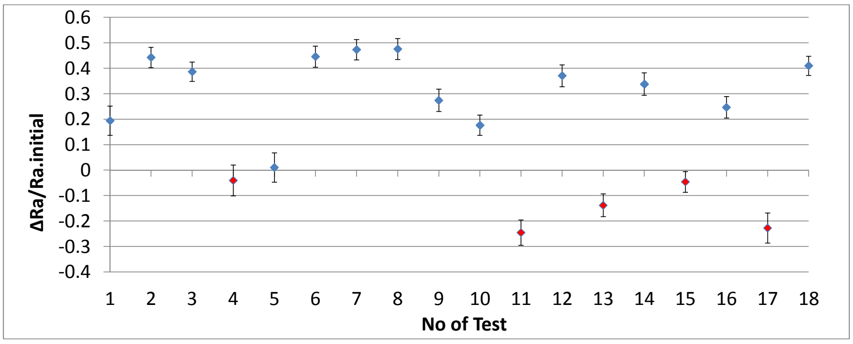

Figure 5. Average values of the ratio of the difference between the initial and final roughnesses over the initial roughness obtained for each test.

such as FFE can be used. The L_{18} orthogonal array for seven parameters with two/ three levels is shown in Table 3 [16].

In this table, S/N is the signal to noise ratio which is used to measure and rank of the importance of the parameters with respect to each other. In these experiments, the final objective is to maximize the ratio of the difference between the initial and final roughnesses over the initial roughness as $\Delta R_a/R_{a.initial}$. Consequently, the S/N ratios for larger-is-better condition are obtained as [16]:

$$S/N_{LB.j} = -10 \log \left(\frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_{ij}^2} \right) \tag{1}$$

where y_{ij} is the measurment of the abovementioned ratio at the ith trail of the jth experiment. Also, n is the total number of trails for each experiment (with these experiments, one has $n = 3$).

5. Experimental tests and preliminary results

In these tests, linear polishing with several passes over a single line is considered. The properties of the workpieces used in this experiment are provided in Table 4. The roughness of the surface along each line is measured before and after the tests. Errors in these measurements are estimated to be less than ± 15 μm (with 95% of confidence level). Next, all these experiments are implements according to the Taguchi orthogonal array and the ratios $\Delta R_a/R_{a.initial}$ are calculated and presented in Table 3 and Fig. 5. In this paper, due to the confidentiality agreement with an industrial partner some information (e.g. initial/final roughness of the workpiece) cannot be provided. In these experiments, the initial surface was not uniform, thus, the $\Delta R_a/R_{a.initial}$ ratios are used instead of the $R_{a.final}$ to interpret the improvement of the surfaces.

Taking into account the ratios of Fig. 5, among all 18 experiments, in test no. 8 the best

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Table 5. Evaluation of the productivity of the process with the preliminary experiments .

Taguchi test no	Polished area (mm^2/min)	Feeding rate (gr/mm^2)	Power (watt)	Energy/area (J/mm^2)	$\Delta R_a/R_{a.initial}$ (Mean)
1	120	2.5	1161.49	580.74	0.194
2	60	13.333	2499.12	2499.12	0.442
3	40	30	4139.80	6209.7	0.386
4	40	7.5	2499.12	3748.68	-0.040
5	120	6.667	4139.80	2069.9	0.010
6	60	20	1161.48	1161.48	0.446
7	40	7.5	4139.80	6209.7	0.473
8	120	6.667	1161.48	580.74	0.476
9	60	20	2499.12	2499.12	0.273
10	120	2.5	4442.88	2221.44	0.176
11	60	13.333	7359.64	7359.64	-0.245
12	40	30	2064.86	3097.29	0.370
13	60	5	2064.86	2064.86	-0.138
14	40	20	4442.88	6664.32	0.338
15	120	10	7359.64	3679.82	-0.046
16	60	5	7359.64	7359.64	0.247
17	40	20	2064.86	3097.29	-0.228
18	120	10	4442.88	2221.44	0.409

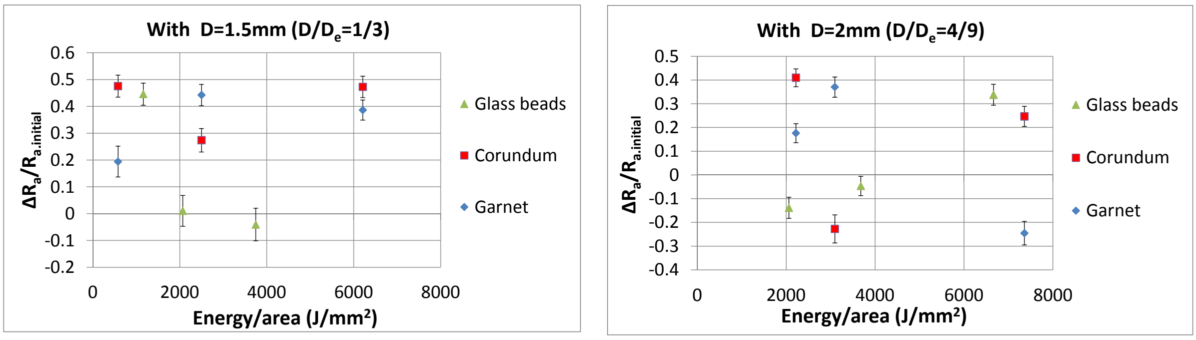

Figure 6. Relationship between the used energy and improvement in the roughness of the surface $\Delta R_a/R_{a.initial}$, (up) with D=1.5 and (down) with D=2 mm.

improvement was obtained. Additionally, with polishing parameters used in tests no. 6, 7, and 8, the lowest roughnesses were achieved respectively around 2.30, 2.26, and 2.13 μm.

With the ejector throat used in these experiments, the appropriate pitch distance is estimated to be 4 mm. Knowing this distance, traversing speed of the nozzle, and the number of passes, the area of the polished surface per minute is calculated. Then, it is used to estimate the amount of consumption of the abrasives and energy (and so power) per square millimeter and the results are provided in Table 5. Afterwards, the relationship between the energy consumption per square millimeter and the improvement in the quality of the polished surface is investigated. This evaluation is done for each abrasive type independently and the results are provided for each nozzle diameter separately, in Fig. 6. The two diagrams presented in this figure cannot show any correlation between the energy and quality of the surface. Because, with seven input parameters, the number of the tests implemented in Taguchi method is not enough to describe this relationship. Therefore, a full-factorial investigation only on the most important parameters is needed to better observe these relationships.

Table 6. Response table for S/N Ratios obtained for $(\Delta R_a + c)/R_{a.initial}$.

Level	D	A	W	N	S	P	T
1	-4.243	-7.849	-7.881	-18.019	-7.014	-12.818	-6.269
2	-14.271	-9.574	-14.923	-6.186	-6.083	-4.975	-10.072
3	—	-10.348	-4.967	-3.566	-14.674	-9.978	-11.43
Delta	10.027	2.499	9.955	14.453	8.591	7.844	5.161
Rank	2	7	3	1	4	5	6

After designing the experiments and performing the tests, the analysis of variance on the results is done. In eq. (1), only the magnitude of $\Delta R_a/R_{a.initial}$ is considered to calculate the S/N value while in the results, there are also changes in the signs of the ratios. Therefore, by adding the constant $c > |\Delta R_{a.min}|$ to ΔR_a, as $(\Delta R_a + c)/R_{a.initial}$, all these ratios will have positive values. Then, the S/N_{LB} ratio is used to determine the importance of polishing parameters on the results of the experiments. As presented in Table 6, these ratios are used to rank the parameters form the most to the least important ones. The difference between the highest and lowest values of the S/N ratios calculated for each parameter shows the effect of that parameter on the results (i.e., higher the difference, higher the importance of that parameter). Consequently, Table 6 reveals that nozzle angle (N), the nozzle diameter (D) and the abrasive feeding rate (W) have the highest impact on the results. However, as mentioned earlier, the Taguchi method does not reveal the optimal values of the parameters.

The analysis of variance of the results shows that these experiments can reveal the effect of the parameters D and N on the results with 90% of confidence. But, for other parameters, the errors in describing their importance are beyond this confidence. This issue does not mean that the DOE in wrong, on the other hand, it only cannot properly describe the effect of these parameters on the results.

6. Conclusion and future works

In this paper, an experimental investigation have been done on the abrasive waterjet polishing process to evaluate its capability in polishing of edges and surfaces of hydraulic turbine blades. For this, the properties of this technique were studied and the main parameters affecting its performance were determined. Then, an experimental test-rig was designed, manufactured and tested to be used in this investigation. Next, the Taguchi method was used to design the preliminary experiments. All experiments were implemented according to the Taguchi L_{18} orthogonal array. The results of these experiments can be used as a basis to design a more precise DOE in which the optimal values of each parameter can be estimated. Considering the maximum amounts of S/N ratios presented in Table 6 , it seems that D1 and N3 (parameter+level) can result in better roughness with 90% of confidence level. Therefore, they are considered as the most important parameters to be used in the future DOE with their most preferred levels. Additionally, the results show that W3, S2, and P2 may be the other parameters and levels to be used in the design of future tests. But, with this model cannot predict the effect of A and T on the process.

In future experiments, by fixing the polishing parameters around the suggested levels, the effect of each parameter is individually investigated. Afterwards, using only the most important parameters, full-factorial experiments can be implements to obtain the optimal values of these parameters which provide the best quality of the surface while the consumption of energy and abrasives are kept at minimum.

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