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Research on the Surface Roughness of Hardox Steel Parts Machined with an Abrasive Waterjet

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This paper presents an experimental investigation on the abrasive waterjet machining (AWJM) of Hardox steels. A full factorial plan was designed and carried out to determine how the traverse speed, the material thickness, and the material type influence the surface roughness. Two materials were machined during the experiments: Hardox 450 and Hardox 500. The experimental data were analysed using statistical methods, and a mathematical model was obtained. Additional experiments were made to validate the model. The results proved that the analysis is accurate and the mathematical model will be a useful tool in industrial environments for process planning when abrasive waterjet machining is used for the considered material.

Keywords: abrasive waterjet machining, Hardox steels, surface roughness, regression model

Highlights

- *Machining of Hardox steels is rather difficult using conventional cutting methods.*
- *This research proved that machining Hardox steels by abrasive waterjet cutting can be an effective method for manufacturing parts made from such materials.*
- *This paper presents the results of experimental research for revealing the correct values of the working parameters when using abrasive waterjet cutting for Hardox steels.*
- *The research used a full factorial plan of experiments followed by a statistical analysis and a proposal of a mathematical model of the roughness variation on three parameters of the process.*

0 INTRODUCTION

In recent decades, one of the manufacturing processes with a significant growth rate is abrasive waterjet machining (AWJM). This was determined by some practical advantages of the method, which makes it a proven flexible manufacturing process [1] to [3]: capability of cutting almost any type of material, no thermal influence, small cutting forces, easy and fast setup, and environmentally friendly.

The process is based (Fig. 1) on using highly pressurized water (1) guided through a small calibrated orifice, named "nozzle" (2), and mixed with fine abrasive particles (5) in a mixing chamber (3). The abrasive jet is then sent through a focusing tube (4), towards the surface of the material (6), which is fixed on slats (7) [1] and [2]. The high speed of the abrasive jet creates enough force to cut through the material of the part.

The dynamics of the process are highly complex. Research studies have been conducted to analyse the influence of process parameters on the surface quality and the precision of parts machined by AWJM.

Usually, the researchers consider the main parameters of influence [4] to [6] to be the following: the traverse speed (TS), the water pressure (WP), the abrasive flow rate (AFR) and the abrasive type, the standoff distance (STD), the material thickness (MT) and the material mechanical properties (MP).

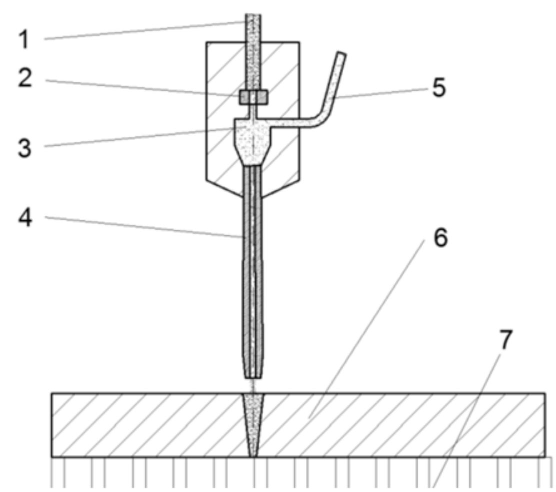

Fig. 1. *Principle of abrasive waterjet cutting*

The TS and the WP are the most researched parameters. It is well demonstrated that for any type of part material – stainless steel [4], [6] and [7], brass [4], aluminium alloys [4] and [8] or titanium alloys [5] – the decrease of the TS improves the surface quality, but increases the manufacturing time and, consequently, the cost. However, for each type of part material, the mathematical dependence between these

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parameters is different and cannot be included in a single model.

The surface quality of a part machined by AWJM is also one of the output parameters that was analysed in scientific works [9] to [13]. It is defined by two major characteristics: the roughness and the geometry.

The effects of some process parameters (MT, TS, AFR) on the surface roughness [9] and [10] of aluminium plates were investigated. However, there was only one type of material used, and a mathematical model was not assessed.

Other studies have used Taguchi [11] and the design of experiments (DOE) techniques [12] to outcome mathematical models of the selected roughness values depending on input parameters, such as TR, WP, AFR, and STD. However, both research studies stated that the models are valid only for the materials used, aluminium alloy or, respectively, specific alloyed steel.

An interesting approach was made using an on-line vibration monitoring method [13]. The research stated that the increase of TS increases the roughness values and the vibrations signal. The mathematical models proposed can be valuable for predicting the selected roughness values according to the vibration signal collected online. However, like other studies, the models are valid only for the material used: a stainless steel.

The surface geometry has also been explored [14] to [18]. Due to the dynamics of the abrasive jet of water, the cut kerf results tapered, with unparalleled walls (Fig. 2), having a so-called V-shaped taper. For the most typical shape of the kerf (Fig. 2), the dimension on the face where the cutting jet enters the material (EN_D) is higher than the one obtained at the surface where the cutting jet exits the material (EX_D). This phenomenon was mathematically modelled by both scientific research [14] and [15] and equipment manufacturers who attempted to compensate it by using a so-called "dynamic jet" [1] and [3]. However, the phenomenon remains when the equipment has a usual cutting head without dynamic tilting of the waterjet.

More in-depth research was conducted to analyse the surface topology alongside the material thickness. One study [16] proposes a whole quantitative parameter that models the dependence between the input parameters (TS, MT, AFR) and the output ones (the surface roughness). The conclusions mention that further research is needed to generalize the model achieved. The topology of the cut zones was investigated in research [17] and [18], for AWJM of stainless steel parts. New methods for estimating the surface quality were proposed based on experimental analysis of the surface profile.

The state of the focusing tube has been also studied [19]. The most critical parameter of influence was determined to be the surface roughness of the tube. Its increase amplifies the cavitating phenomenon, which has a negative influence on AWJM efficiency.

The research previously mentioned, made in the field of AWJM, stated that the validity of the results is limited mainly to the type of the tested material and the particular conditions occurring during those tests. Consequently, if a new material is supposed to be machined by AWJ, the selection of proper technological setup to obtain a specified certain surface quality is based only on similar materials previously evaluated. If the results are not satisfactory, the trial-and-error method is recommended.

This paper presents a scientific approach of the above issue when using AWJM for the material family of Hardox steels [20] and [21].

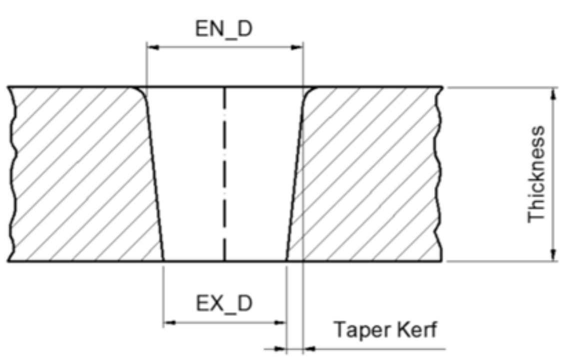

Fig. 2. *Taper kerf occurrence*

Manufacturing of parts made of Hardox steel alloys is usually challenging to be machined using traditional cutting processes because of their chemical composition. Such materials have high abrasion resistance and an elevated hardness.

Abrasive waterjet cutting of Hardox steels has been investigated. The influence of the primary process parameters (TS, AFR, STD) was evaluated [22] to [24]. The research has demonstrated that the traverse speed is the most significant process parameter that influences the surface quality of the part. At the same time, like for other metal alloys, the best water pressure values have to be the highest possible. However, each paper considered only one value of the material thickness or one type of material; therefore, these parameters of influence were constant during the experiments.

A comparison between plasma, laser cutting, and AWJM [25] has indicated that AWJM gives the most positive results in terms of surface quality.

Based on the literature review and some of their studies [26], the authors considered the need for more comprehensive research on using AWJM for the Hardox steels family. The research was initiated within a project required by an industrial company which manufactures parts made of Hardox steels by AWJM. Their need was to determine the proper setup to obtain the specified quality parameters. A mathematical model has been developed, analysed, and validated. This model can be further used by the machine operator to select the proper value of the input parameters, so the output surface quality will result as required in practice.

1 EXPERIMENTAL SETUP AND METHOD

The equipment used in the experimental activities was a Maxiem waterjet cutting machine, having a 20 HP pump and a maximum water pressure of 350 MPa. The dynamics of the machine does not allow the possibility of automatic tilting, to compensate for the V-shaped taper effect. The abrasive feeding system is a regular one, with a constant feed rate, which was carefully measured before the experiments.

The main goal of the experimental research was to establish the laws of influence of the process parameters on the surface quality of parts from Hardox steels, machined with an abrasive waterjet.

Three input variables were selected:

A. type of material;
B. traverse speed;
C. part thickness.

The selection of these three input variables was based on the following considerations:

- water pressure directly influences the process productivity and costs; almost all studied research agrees that it is better to use the maximum values given by the equipment;
- equipment used for AWJM has a constant abrasive dosing system;
- previous research of the authors [26] proved that the standoff distance has a lower influence on the process, and the equipment used for experiments does not have an automatic standoff setup;
- previous research of the authors proved that the main parameter is the traverse speed, as also stated by all experiments done by others.

According to the above statements, the values of the constant parameters were adopted, as seen in Table 1.

Table 1. *Values of the constant parameters used during the tests*

Name of parameter	Units	Value
Water pressure	MPa	350
Abrasive flow rate	g/min	350
Abrasive type	mesh	80
Water nozzle diameter	mm	0.279
Focusing tube diameter	mm	0.838

Two types of Hardox steel were tested; they have the mechanical properties presented in Table 2 and the chemical composition in Table 3.

Table 2. *Mechanical properties of the materials* [21]

Material grade	Hardox 450	Hardox 500
Hardness HBW Brinell	425 to 475	470 to 530
Yield strength [N/mm^2]	1200	1300
Tensile strength [N/mm^2]	1400	1550

Table 3. *Chemical composition of the materials* [21]

Material grade	Hardox 450	Hardox 500
C [%]	0.23	0.30
Si [%]	0.70	0.70
Mn [%]	1.60	1.60
P [%]	0.025	0.020
Cr [%]	1.20	1.50

The usual recommendation in such type of experiments is to plan a full factorial design [27]. Two levels were adopted for each of the three factors. The standard orthogonal matrix L8 (2^3) is shown in Table 4, and the values of the levels can be seen in Table 5. Those values were decided based on previous research in the field [26] and by practical reasons of the industrial company.

Table 4. *Matrix of the experiment, L_8 (2^3)*

Run order	Factor		
	A	B	C
1	-1	-1	1
2	1	-1	-1
3	-1	1	1
4	1	1	1
5	1	1	-1
6	-1	1	-1
7	-1	-1	-1
8	1	-1	1

Table 5. *Levels of the variable parameters*

Code	Process parameter	Units	Level 1	Level 2
A	Material type	n.a.	Hardox 450	Hardox 500
B	Traverse speed	mm/min	30	70
C	Material thickness	mm	12	20

Each experiment was repeated three times for improving the statistical confidence of the data.

After the trials, each part was analysed in terms of surface quality. The linear cut surface of some parts is presented in Fig. 3, showing the measuring procedure. The roughness was measured with a portable Mitutoyo SJ210 Surftest tester (Fig. 4), at the middle of the linear face of each part, approximately at 4 mm from the edge, both on the upper side and the bottom one. The values were measured on the linear region of the part because in this region the traverse speed is constant with the values according to Table 5.

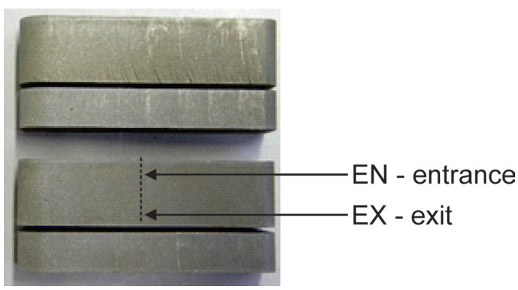

Fig. 3. *View of the cut surface with the measuring zone*

Fig. 4. *Measuring equipment for the roughness*

For the evaluation of the surface roughness, the R_a parameter was used because it is by far the most common in both industry and research. The R_a parameter, being the arithmetical mean deviation of the assessed profile [28] and [29] can be considered of universal use and a very reliable parameter.

The measured values of the surface roughness parameter R_a, both at the entrance and the exit sides, for the three samples of each test (P1, P2 and P3) are presented in Table 6. The arithmetic mean values were also calculated in the last column of Table 3.

Table 6. *Values of the measured roughness R_a on the parts*

Run order	Side	P1	P2	P3	Mean
1	entrance	2.085	2.388	2.228	2.300
	exit	2.192	2.145	2.402	2.246
2	entrance	2.500	2.424	2.585	2.503
	exit	2.708	2.375	2.789	2.624
3	entrance	2.414	2.283	2.431	2.376
	exit	2.361	2.410	2.671	2.480
4	entrance	2.624	2.953	2.538	2.705
	exit	7.095	5.208	6.060	6.121
5	entrance	2.611	2.860	2.686	2.719
	exit	6.981	7.282	6.588	6.950
6	entrance	2.110	2.179	2.435	2.241
	exit	2.739	2.526	2.805	2.690
7	entrance	2.193	2.103	2.231	2.175
	exit	2.288	2.398	2.395	2.360
8	entrance	2.471	2.838	2.278	2.529
	exit	2.737	2.794	2.833	2.788

2 ANALYSIS OF EXPERIMENTAL RESULTS

As stated, the main goal of this research was to establish a mathematical model for predicting the correct value of the surface roughness depending on the input parameters during the waterjet machining of Hardox steels. To achieve the goal, a full factorial experimental plan was realized. Three input variables were considered: the traverse speed, the material thickness and the material type. For each variable, two levels were considered. The output parameter was the surface roughness.

It is well known that there is a difference between the values of the surface roughness on the entrance and the exit areas of the part. This difference can be significant for certain combinations of values for the traverse speed and the part thickness. It can be stated that usually the values on the exit side are greater than the ones on the entrance. In terms of quality characteristics, the critical values of the surface roughness are on the exit side – the bottom side of the part, as they are all greater than the values on the entrance side – the upper one (see Table 5).

The statistical analysis was done by using Minitab software **[30]**.

An essential aspect of the statistical analysis is to quantify the amount of influence of each parameter on the process output. This is usually achieved through the analysis of means (ANOM). For the roughness values, the results are presented in Fig. 5. According to the diagrams, the traverse speed and the material thickness have a significant influence on the surface roughness compared to the material type, which can be statistically neglected.

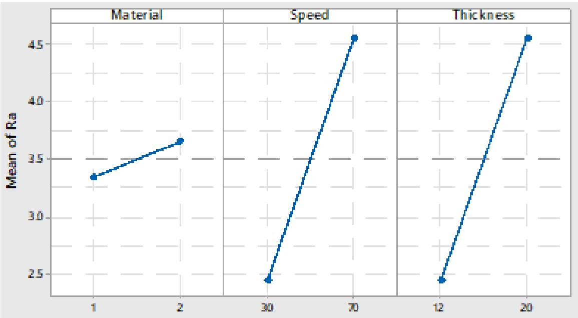

Fig. 5. *Analysis of means for roughness* R_a

It is also essential to analyse the interaction between the input parameters. These diagrams are shown in Fig. 6.

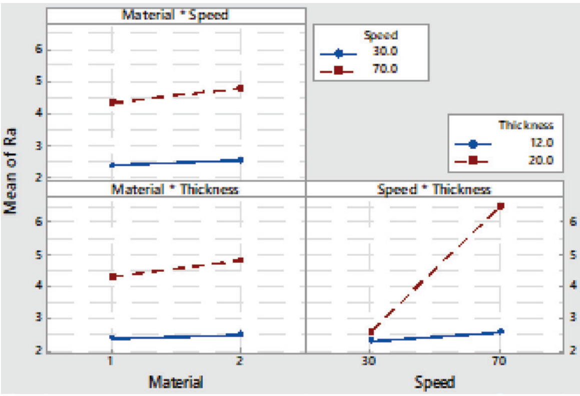

Fig. 6. *Interaction diagram for roughness* R_a

The amount of interaction can be evaluated by the Pareto diagram of standardized effects of the input parameters (Fig. 7).

According to these diagrams, the material thickness (Factor C) and the traverse speed (Factor B) are the most significant parameters of influence, in this order of importance. The material type (Factor A) has a minimal influence. The interaction Factor B/ Factor C is important, while the interactions A/B and A/C are relatively small.

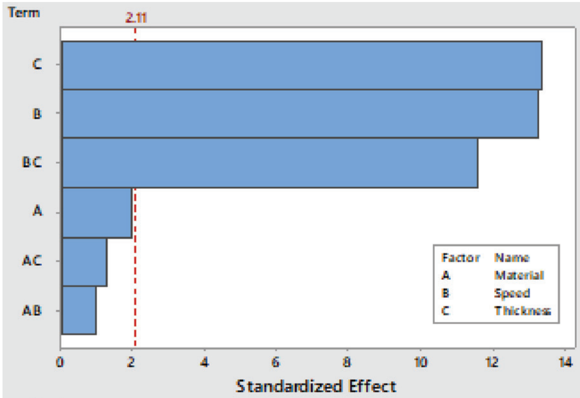

Fig. 7. *Pareto diagram for the roughness* R_a

Based on the above statements, a regression that takes into consideration the interaction B/C was analysed. The global equation is:

$$R_a = K - 0.1311 \cdot B - 0.3095 \cdot C + 0.01149 \cdot B \cdot C. \quad (1)$$

In Eq. (1), the factor K is a constant, and its possible values are presented in Table 7.

Table 7. *Values of the factor* K *in Eq. (1)*

Equation type	Value of K
Global	5.812
Hardox 450	5.656
Hardox 500	5.948

The statistical analysis of the global model is presented in Table 8. The R-squared (R^2) value of 95.41 % and the P-value of lack-of-fit of 0.167 lead to the conclusion that the model can be used to predict the values of the process parameters.

Table 8. *Statistical parameters of the regression model*

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	3	74.021	24.6735	138.61	0.000
Linear	2	53.738	26.8691	150.94	0.000
Speed	1	26.757	26.7569	150.31	0.000
Thickness	1	26.981	26.9812	151.57	0.000
2-Way interactions	1	20.282	20.2823	113.94	0.000
Speed* thickness	1	20.282	20.2823	113.94	0.000
Error	20	3.560	0.1780		
Lack-of-fit	4	1.130	0.2826	1.86	0.167
Pure error	16	2.430	0.1519		
Total	23	77.581			

3 VALIDATION OF PREDICTED MODEL

The validity of the mathematical model acquired in Eq. (1) was evaluated with four experiments that were carried out in the same conditions assumed during the main experimental research. The machining was done on the same equipment, and the values of the constant parameters were those mentioned in Table 1. For each experiment, two parts were manufactured. The results are presented in Table 9.

The predicted values of R_a considered in Table 9 were calculated with Eq. (1). The mean values of R_a measured after the experiments were calculated using the values of the exit side of the part since the regression model was calculated assuming the same hypothesis.

The difference between the predicted and the obtained values of the roughness are presented in the last column of Table 9. These values have to be within a confidence interval, calculated based on the mean square error of the statistical data (see Table 8).

The usual confidence interval (CI), corresponding to $1-\alpha$=95 % confidence level of each estimated effect **[27]**, is:

$$CI = \pm z_{\alpha/2}\frac{\sigma}{\sqrt{n}} = \pm 0.1687. \qquad (2)$$

In Eq. (2), the factor $z_{\alpha/2}$ is the 2.5 % quantile of the standardized normal distribution; σ is the estimated value of standard deviation and represents the number of experimental sets of values used in the research.

The analysis of data presented in Table 9 shows that all values are within the confidence interval given in Eq. (2). This fact is also proved in Fig. 8, which shows the graphical comparison between the predicted (calculated) and the measured (tested) values of the roughness R_a, for Hardox 450 steel, when the traverse speed TS = 50 mm/min.

Table 9. *Data of experiments made for validation*

Test no.	1	2	3	4
Material type	1	2	1	2
Traverse speed [mm/min]	50	50	50	50
Material thickness [mm]	20	20	12	12
Roughness R_a EX	4.391	5.281	2.837	2.529
	4.996	3.792	2.234	2.248
Roughness R_a EN	2.988	2.470	2.761	2.625
	2.279	2.822	2.163	2.074
Mean R_a [µm]	4.690	4.540	2.540	2.390
Predicted R_a [µm]	4.560	4.560	2.440	2.440
Variance [%]	–3.0	0.4	–4.1	2.0

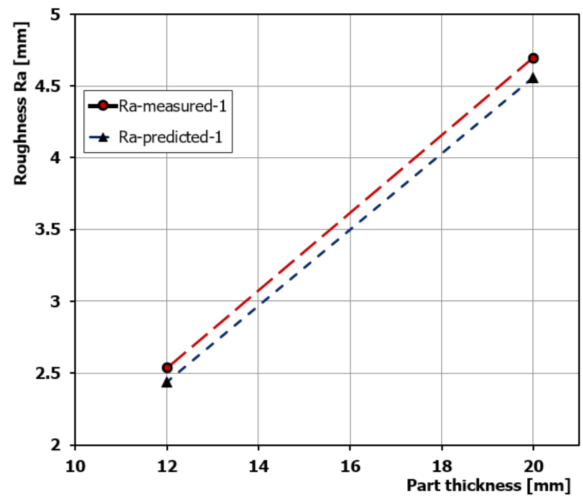

Fig. 8. *Comparison between predicted and measured values of roughness R_a*

4 CONCLUSIONS

Experimental research has proved that special steels, like Hardox, can be machined by abrasive waterjets with real advantages on other machining processes. The main issue is to choose the proper values of the input parameters to obtain the desired ones of the output parameters.

For this type of material, an orthogonal experimental plan was designed and conducted. Three input variables were selected: the traverse speed, the material thickness, and the material type. The output parameter was surface roughness.

The results demonstrated that the material thickness has the most significant influence on the surface roughness. The traverse speed has the second greatest influence on the surface roughness, and the material type has minimal influence. The surface roughness increases when the material thickness increases, and when the traverse speed increases.

The model of regression that predicts the influence of parameters is a nonlinear one. The global model, seen in Eq. (1), which predicts the output parameter for the two materials tested has a good confidence level, demonstrated by the experiment's validation. However, a higher level of confidence is achieved by using a specific regression for each material. It must be pointed out that this model is valid within the range of variation of the input parameters used during the experimental tests.

Further research will be developed to extend the validity of the regression model for other values of the material thickness and other types of steels with high toughness when using the technology of abrasive waterjet machining. In the research, genetic programming algorithms will also be used [31] to optimize the AWJM parameters.

5 ACKNOWLEDGEMENTS

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