Optimum Parameters for Cutting Hard and Tough Material (Hardox Steel) by Abrasive Water Jet Cutting Process

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Abstract: Nowadays, the non-traditional processes such as LASER, EDM and AWJ, are used for cutting high thickness sheet metal. Hardox is hard and tough steel alloy and it has many industrial applications. One of the best processes to cut the Hardox is abrasive water jet (AWJ) cutting. It can cut complex shapes with high quality and accurate tolerances. AWJ cutting offers certain unique benefits such as negligible heat affected zone, high degree of manoeuvrability in cutting process and less machining force exertion. In this research work, first, the effective cutting process “AWJ” parameters were identified. Then, to determine optimum Hardox cutting parameters, some experimental tests were undergone. Finally, the experimental results were analysed using “ANOVA” technique in order to determine regression equations for achieving optimum parameters to set-up equipment for Hardox steel cutting.

Keywords: AWJ cutting, Hardox steel, Analysis of variance, Regression model

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1 INTRODUCTION

The cutting process with abrasive water jet is a new cutting method for cutting hard materials without any limitations in the work piece material. In this process, water passes through a very small orifice with 4000bar pressure and creates high speed water jet in mixing chamber. During the process, abrasive particle is added and abrasive water jet enters the nozzle with the air and leaves the nozzle as a mixture of water, abrasive particle and air.
While the abrasive particles hit the work piece surface with high kinetic energy, the material removal takes place [1-3]. The prominent specification of the abrasive water jet cutting process is without heat affected zone (HAZ) and mechanical stress in the cutting location [3]. In Fig. 1 a comparison of applying different cutting methods for various work piece thicknesses is provided.

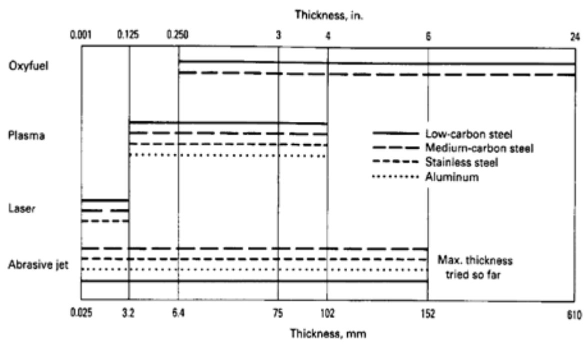

Fig. 1 Comparison of applying different cutting methods for various work piece thicknesses [2]

In recent years, researchers have tried hard to come up with a definite relation in order to determine the optimum cutting parameters for different materials [4]. However, no exact mechanism is found yet for material removal, because there isn't a clear reason for defects in the cutting location. Based on Hashish [5], the resultant defects in the cutting location which is known as the striation zone, is an internal feature of the process due to the mechanism changes of the wear by the abrasive particles, which is a change of cutting mechanism to deformational mechanism.
In cutting with abrasive water jet, the cutting surface is identified by two areas, as shown in Fig. 2 [6]. The first zone is a smooth and defect-less surface where the second zone is beneath, an irregular and rough surface with tapper angle.
The second zone is called the striation zone, in which there are some defects like increasing the surface roughness, kerf tapering and burr [5], [6]. Regarding the striation zone, in addition to the Hashish, some other theories including the vibration effects of the machineries, are provided [7], [8].

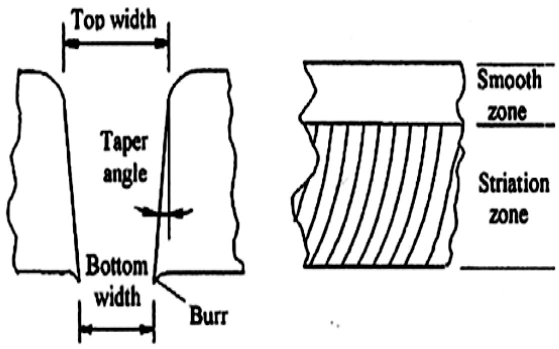

Fig. 2 Schematic and definition of kerf geometry [6]

H. Orbanic and et al. performed a simulation of the striation zone by collecting some striation reasons and practical experiments [9]. They could show the fluctuation wave in the striation zone by high speed scanning. Major manufacturers of the abrasive water jet cutting machines have suggested some limited materials for their optimum settings (regardless of their characteristics in the heat treatment influences) in their catalogues and for new materials which they suggest the test-and-trial method.
The work piece material has a great influence on the optimum parameters setting and achieving these optimum features through test and trial, depends mainly on the operator' experience and is not necessarily a scientific method.
In 2010, F. Bouda and et al. practically determined the effects of the abrasive particles using different materials such as alumina, Garnet, glass particles and steel particle on titanium [10]. Their main conclusion includes the influence of the abrasive particles hardness on reducing the lining area. These days Garnet particles are commonly used as the particles with high hardness and reasonable price.
In this study the effects of TS, AFR and the water pressure in cutting Hardox Steel (a metal with high hardness and toughness) is determined. Subsequently, using a regression method, the optimum cutting parameters are provided. To analyse and determine the optimum parameters, Minitab software is used to provide the optimal conditional. Considering a quality parameter such as surface roughness on the cutting surface, the maximum allowable traverse speed rate is determined.

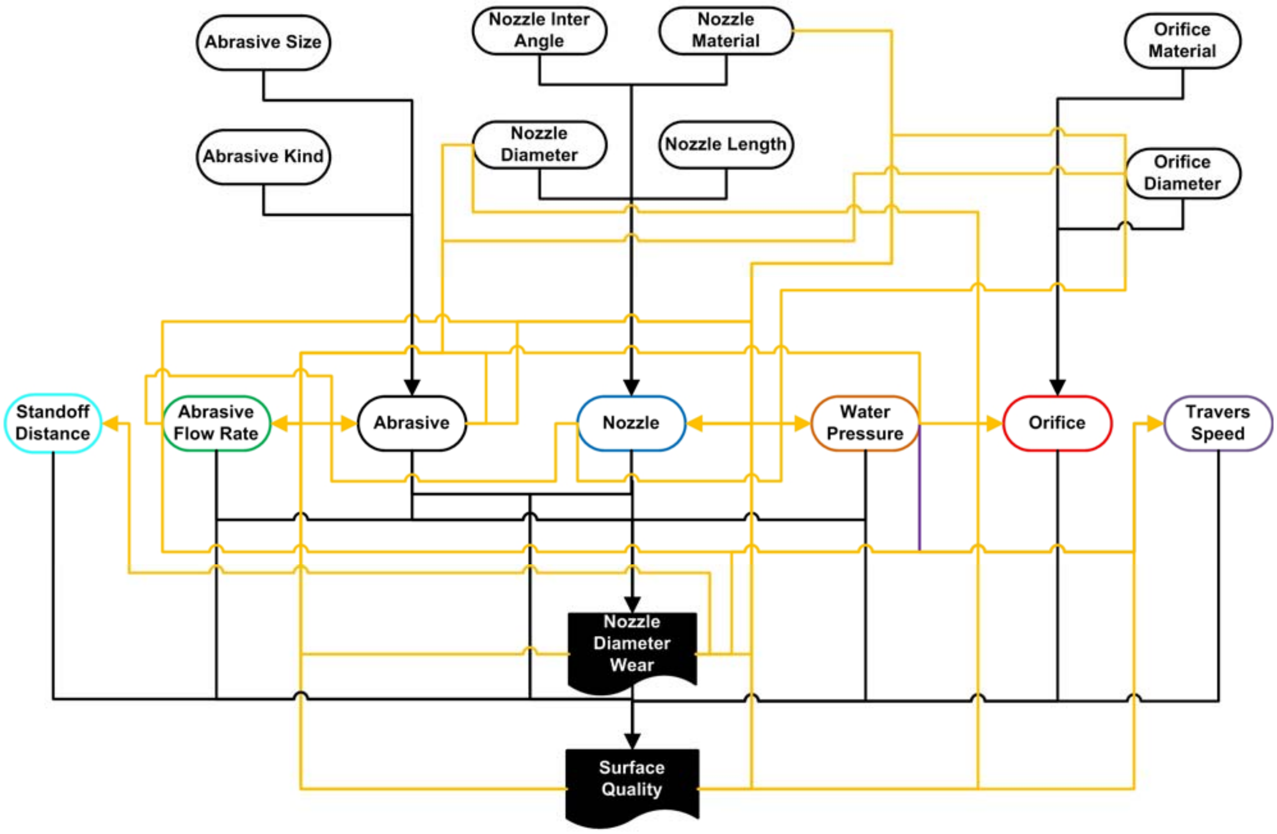

Fig. 3 Relation between different parameters in AWJ machining process

2 RECOGNIZING THE COMMON INFLUENTIAL PARAMETERS ON THE KERF

Like the common abrasive water jet cutting machines, the influential parameters in the process which are not fixed are presented in Fig. 3. The Chart in Fig. 3 are allocated for demonstrating the effect and influence of the parameters in optimal setting based on the gradual increase in the nozzle diameter and the surface quality of the kerf. Next by obtaining the influence of all the parameters in cutting a special material, the optimum setting is given.

In this chart the black (dark) lines show the influence path of the all parameters on the nozzle wear and the final quality, and the grey lines (light) show the influenced direction of the given value for each parameter from the other ones. The depicted parameters in the third row are easy to change in the typical machines and the parameters in the first and second row are the influential parameters in determining the initial value of the unfixed parameters. In workshops, generally the orifice, nozzle, material and the abrasive particle size are fixed and just some parameters like P, AFR, standoff distance (SOD) and traverse are changed. The SOD to the work piece for cutting the metals should be in the range of 0.5 to 1.5 mm [6].Then the parameters which are tested for determining the optimum cutting condition, are the followings: water pressure, abrasive flow rate and traverse speed.

3 HARDOX STEEL PROPERTIES

The Hardox Commercial steel, with chemical and mechanical properties given in Table 1 and Table 2, has a high toughness and hardness being greatly applied in sensitive industries. Hardox sheets are a type of carbon steel water quenched material, which their hardness is the same from the surface to the centre. Recently these sheets with 40-55 RC the hardness, have found great applicability in industries, and are mostly used for anti-wearing applications [11].

Hardox steel is mostly applied in places where great resistance to wear is needed, which their prominent property is great resistance to fracture in low temperatures (compared to common steels). Those materials which should be more resistant to the impacts in low temperatures are completely sensitive. The old methods in cutting Hardox material in Iran include cutting by plasma or gas which is not sufficient for the required sensitivity and accuracy. Cutting the Hardox pieces by AWS does not provide the heat affected zones (HAZ) and regarding the low cutting energy which is applied to the work piece, then no expensive big jig fixtures are needed for cutting big wok pieces.

Table 1 Chemical Properties of Hardox steel (Thickness=25mm) [11]

C	Si	Mn	P	S	Cr	Ni	Mo	B
0.23	0.7	1.6	0.025	0.01	1	0.25	0.25	0.004

Table 2 Mechanical Properties of Hardox steel [11]

Mechanical property	Value	Unit
Hardness	450-475	HBW
Yield strength	1200	N/mm^2
Tensile strength	1400	N/mm^2
Elongation A50	10	%

4 EXPERIMENTAL PARAMETERS SETING AND RESULTS

Table 3 is the set parameters for the experiments. AWJ cutting machine is from KMT Company with MOST-2D SINUMERIK D810 model with full factorial design. The work piece used for experiment is a uniform block with 25mm thickness and 12 parts were cut with different setting parameters. By performing the experiment, different measurements were made and analysed as follows:

The roughness of the cutting surface along the cutting direction, in the upper, intermediate and lower sections of the Kerf, and the width in the lower and upper sections of the Kerf were tested and analysed. For this purpose surface roughness was measured by German Mahr machine, Perthometer M2 Model, with 0.0005µm accuracy. Fig. 4 shows the kerf width above, and below the workpiece in terms of TS. It also shows that with increasing TS, kerf width variation above the kerf is less with respect to the below, and if the workpiece thickness remain constant, increasing TS may lead to more tapering.

Table 3 Machining settings used in the experiments

Parameters	Unit	Value
Traverse Speed (TS)	mm/min	15, 30, 45
Water Pressure (P)	bar	3500, 3800
Abrasive Flow Rate (AFR)	g/min	300, 400
Orifice Diameter (Do)	mm	0.33
Nozzle Diameter (Dn)	mm	1.1
Length of nozzle (L)	cm	75
Stand of Distance (SOD)	mm	1.5
Jet Impact Angle( )	Deg	90
Abrasive Size and Type		Garnet #80

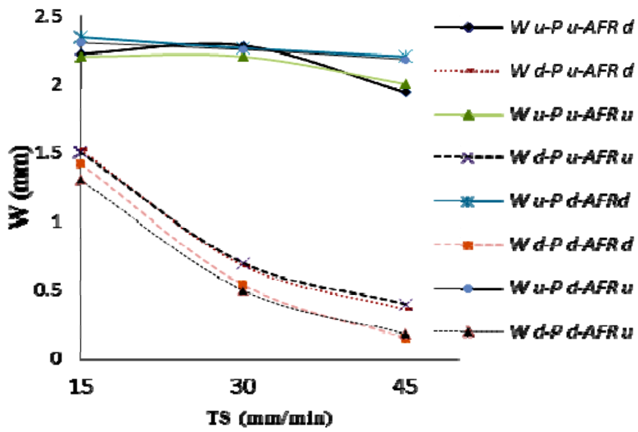

Fig. 4 Diagram of kerf width in the upper and lower sections relation the TS (P_u=3800 bar & P_d=3500 bar and AFR_u=400 g/min & AFR_d=300 g/min)

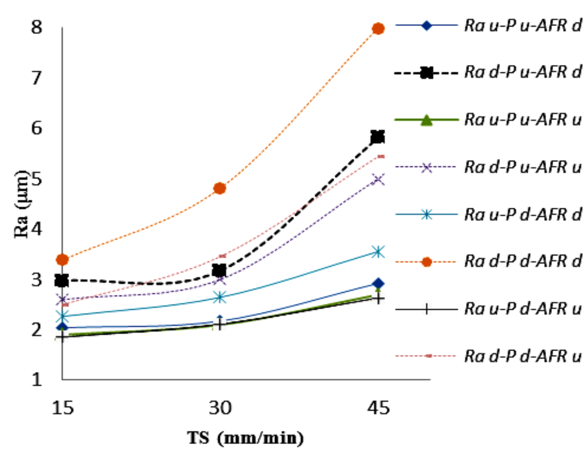

Fig. 5 Diagram of the surface roughness to the TS (P_u=3800 bar & P_d=3500 bar and AFR_u=400 g/min & AFR_d=300 g/min)

Fig. 5 shows the diagram of the surface roughness to the TS. Changes in the surface roughness are greater at the end of the Kerf (striation zone) than its upper part of Kerf (smooth zone).

Fig. 6 shows the tapper angle in the Kerf wall compared to the cutting centre line, where the mean tapper angle is about 88.85º. Decreasing the TS, water pressure, and abrasive flow rate causes the tapper angle to increase. The main reason of the slop in Kerf wall and great surface roughness in the lower section is because of the striation zone. Fig. 7 shows the main influences of the parameters on the surface roughness and accordingly, the water pressure effect and abrasive flow rate are less compared to the TS rate effect.

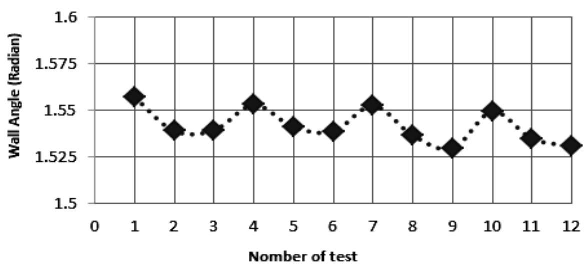

Fig. 6 Tapper angle in the Kerf wall compared to the cutting centre line

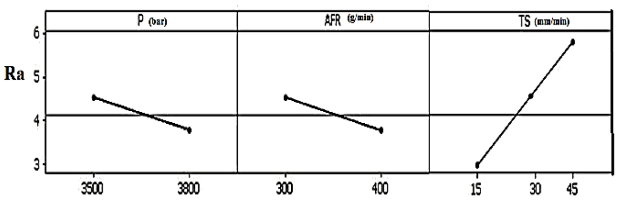

Fig. 7 Effect of major parameters on Ra

5 EXPERIMENTAL RESULTS ANALYSIS

Minitab software and ANOVA analysis were used to analyse the results and determine the optimum values of the parameters. The results indicate that the P and AFR parameters should be kept in maximum and the traverse speed in its minimum in order to achieve the least surface roughness (Fig. 7). But in order to get the maximum efficiency, the parameters settings should be in such a way that the least expenses spent for manufacturing. By analysing the effective factors on the quality and Kerf width, the main parameters affecting the surface roughness are as the followings: TS (67٪), AFR (20٪) and water pressure (13٪). The main factor influencing the Kerf width is the TS, where water pressure has a minor effect. AFR has a slight effect in the Kerf width and it may be ignored. Fig. 8 shows the standardized effect of the parameters on the Kerf width and surface roughness.

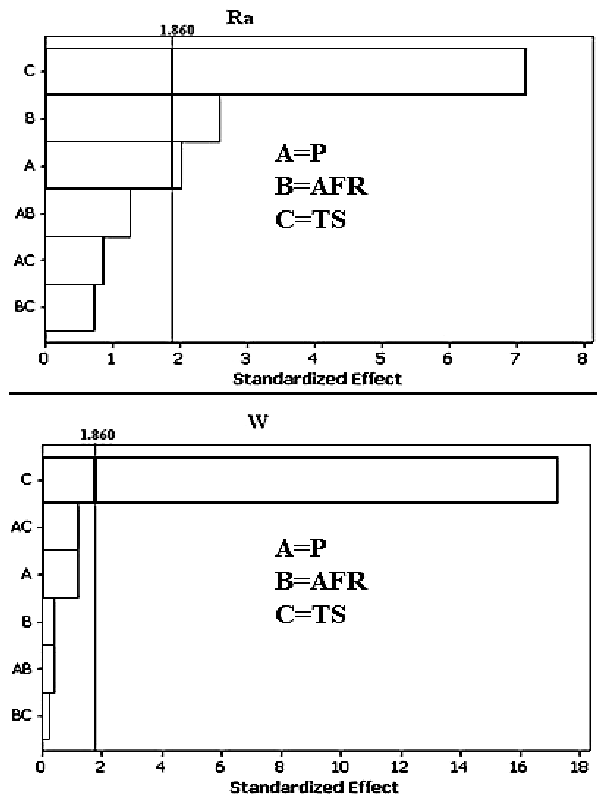

Fig. 8 Standardized effect of the parameters on the Kerf width and surface roughness

During optimization, in order to keep the expenses minimum, the TS should be in its maximum allowable value and in order to decrease the maintenance costs, such as the nozzle wear or the malfunction of the hydraulic parts, the AFR and water pressure should be maintained in their minimum allowable values [12]. Maximum flow rate is necessary to hold cutting operation within an optimum quality. For common machines, the manufacturers have set the pressure to its maximum allowable value, which in the present experiments the pressure changes followed this rule. The maximum AFR depends on the nozzle diameter where its optimum value is related to the orifice and the nozzle diameter proposed by the manufacturers of AWJ cutting machines. The range of the abrasive change rate in the experiments is mainly based on the nozzle and the orifice diameter.

The only remaining factor is the nozzle TS which its optimum value is determined using Equations (1) and

(2), in regression style. Table 4 is the analysis results of Eq. (1) to determine the influential parameters efficiency, which indicates that AFR is not significantly influential. In Eq. (2), the only affecting parameter is the TS which linearly increases Kerf width with a little tapper angle.

$$TS= (Ra-14.8-0.00279 \times P-0.0103 \times AFR) / 0.107 \quad (1)$$

$$W=1.49+0.000194 \times P+0.000194 \times AFR-0.0138 \times TS \quad (2)$$

TS is the traverse speed (mm/min), Ra is the surface roughness (µm), P is the water pressure (Bar), AFR is the abrasive flow rate (g/min), and w is the Kerf width (mm). By determining the work piece tolerance in the surface quality and work piece dimensions, the optimum TS is obtained based on Eq. (1). By applying the optimum TS, the AFR and P are determined in the second equation of the Kerf width that is half of the offset Kerf for applying in CNC machines. Adjusting P and AFR parameters depends on the type of machine, nozzle diameter, and orifice [2]. Moreover improved productivity is achieved by determining optimum speed (TS) using Eq. (1).

Table 4 ANOVA analysis of Eq. (1) to determine the influential parameters efficiency

prospect	coefficient	SE Coef	T	P
Constant	6.053	1.095	5.53	0.000
P	-0.0013538	0.0002867	-4.72	0.000
AFR	0.0013328	0.0008600	1.55	0.131
TS	0.027477	0.003511	7.83	0.000

6 CONCLUSION

The main goal of the present study is to determine a model for forecasting the optimum parameters for cutting Hardox steels with abrasive water jet cutting process. In addition, it may be possible to develop a general procedure for cutting steels using abrasive water jet cutting process. The experimental results show that AFR and P should be in their maximum allowable value and then the TS is given based on Eq. (1), where the tolerance of the optimum surface quality is determined for the workpiece. If the TS is less than its optimum value, more cost is expected because of increase in the cutting time. The Kerf width, as given by Eq. (2), is suitable for CNC machine offset. Manufacturing workpieces with high accuracy and sensitivity is economically possible by these optimum parameters.

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