Al-Khwarizmi Engineering Journal, Vol. 15, No. 3, Sptember , (2019)
P. P. 29- 37

Al-Khwarizmi Engineering Journal

Optimizing the Parameters of Hot-wire CNC Machine to Enhance the Cutting of Plastic Foam

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(Received 23 October 2018; accepted 28 January 2019)

https://doi.org/10.22153/kej.2019.01.006

Abstract

Hot-wire cutting is one of the important, non-traditional thermomechanical way to cut polymer, usually expanded foam and extruded foam, in low volume manufacturing. The study and analysis of Hot-Wire cutting parameters play an important role to enhance the quality and accuracy of the process and products. The effects on the surface have been investigated by using experimental tests designed according to the Taguchi orthogonal array (OA). In this study, four parameters with five levels for each parameter have been used: [temperature of wire (A) (100, 120, 130, 150, 160) °C], [diameter of wire (B) (0.3,0.4,0.5,0.7,0.8) mm], [velocity of cutting (C) (200, 300،400,500,600) mm/min], [and density of foam (D) (0.01,0.027,0.029,0.032,0.037) g/cm^3]. Statistical software (MINITAB17) used to find the optimum conditions, which they are in Material Removal: 100 ˚C, 0.5 mm, 300mm/min, 0.032 g/cm^3.

Keywords: *Hot-wire cutting, polystyrene, foam cutting, taguchi, MINITAB1, material removal.*

1. Introduction

Today the products of plastic are an important and integral part of everything in our life. The process of manufacturing the plastic foam is the casting and extruding, so the perfect way to cut these types of foam is hotwire cutting. This cutting can be performed with a source of heat, which is wire that change the physical properties of material until it can be cut with low cutting force [1]. There are several mechanisms for the cutting of plastic foam; they can be divided into three-basic modes or the mixing among them:

- Thermal cutting: In this mode, the plastic foam is vaporized or just melting in front of the wire cutter but without touching between them. See Figure 1.a.
- Thermo-mechanical cutting: this mode is a mixing between the shearing force and the melting of material to perfume the cutting and the hot-tool in contact with the material. See Figure 1.b.

Mechanical cutting: this mode depends on the shearing because it happens when the temperature of tool is below the melting point of the foam [2]. as shown in Figure 1.c

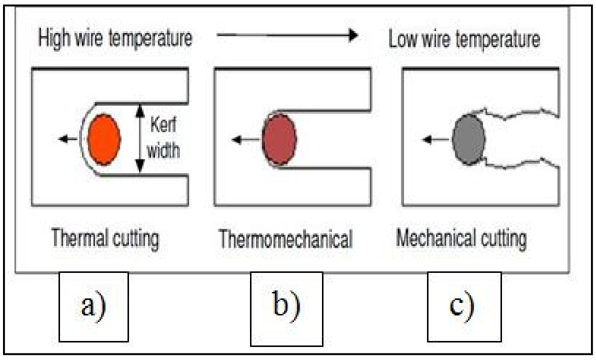

Fig. 1. Cutting mechanism [2].

Simply the principle work is an electrical power pass through wire then the wire is heated to desired temperature degree according to the input voltage through electrical resistance. When the wire contact the surface of foam, it melts the area surrounding it, the heat of the wire vaporises the foam creating a smooth surface Figure 2. shows the wire is moving across the specimen of foam material.

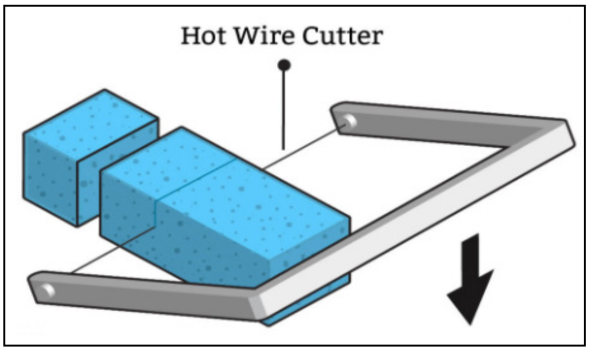

Fig. 2. The hot-wire foam cutter.

The material to be cut is just soften under the point of melting because it is thermoplastic material, after that the cutting is done. The surface of the cut and kerf-width is affected by the changing of the velocity and the diameter of wire even if it was small [1].

Many researchers have studied the cutting process of polymers and the effective parameters on it. Harmanpreet & Manpreet Singh [3] studied the effect of parameters for the polymer cutting process on material removal rate and kerfwidth also the optimization of the machining process. Ranjeet et al [4] maked investigation in ablation process for the Expanded Polystyrene (EPS) rapid prototyping to predict and calculate the kerfwidth and surface roughness (Ra) with mathematical model. Kiril & Jesper [5] proposed a novel thermo-electro-mechanical model for hotwire cutting of EPS foam and predicts the stress, voltage and temperature of wire during cutting of EPS foam. In addition, find relation between kerfwidth and the cutting angle as measured from the horizontal direction. Namrata & Sathyan [6] investigated the factors responsible for the bowing phenomenon via a series of experiments involving variations in current and wire feed rate, build more precise prototypes, kerf width is also examined, Further more finding noval way to predict the influence of gases in bowing has been analyzed and quantified. Luka Ivanovskis [7] developed a 4-axis numerically controlled hot-wire foam cutter suitable for flying aircraft modelling purposes. Numerically controlled foam cutter had to be able to cut intricate shapes out of foam material such as extruded polystyrene by using 3D virtual model, also find novel mathematical model to predict the kerfwidth, and empirical relationship is established to predict the surface roughness (R_a) of the sliced surface by performing regression analysis. Ahn et al [8] studied the Influence of process parameters on the surface Jroughness in hotwire of variable lamination manufacturing (VLM-S) for EPS foam such as cutting angle and compositions of expandable polystyrene EPS, the apparatus is four-axis automatic cutter and the specimen is thin foam. While in my study, parameters differsand the device is 2D axis CNC. with any thickness of foam can be cut. P. Gallina et al [9] studied the hot wire with 2D robotic system to cut polystyrene plates with accurate force control which is delayed reference control (DRC) with time delay: x_d(t-T) ,T the time delay calculated online, while my study is about 2D CNC machine and different parameters to reach optimum conditions of cutting without considering of time.

The objective of this paper is to obtain the optimum cutting conditions for hotwire cutting process, and study the effects of these parameters on the process.

2. Material and Method

2.1 Foam Used in Hotwire Cutting

Extruded Polystyrene (XPS) foam is used in this study with different densities. Foam is a combination of polymer solid phase and gas mixed together in high speed until it become as smooth as desired. The applications are virtually endless, ranging from items as small as a kitchen sponge to a soundproofing systems in cinemas [10].

2.2 Implementation of Parts of the Machine

The machine is very easily adjustable and therefore it is expected to provide a possibility for high accuracy, with specifications as shown in table 1. The two stepper motors as shown in figure 3 make together the movements of the two axes X and Y, which are vertically and horizontally standing. The motors velocity of hotwire CNC machine adjusted by the Universal G code sender software (which is platform of G-code with full featured used to interface between motors of CNC and the computer) as shown in figure4, through the ARDUINO-UNO shown in figure5 [11].

Table 1,
specifications of CNC machine

No. of CNC axes	2 a xis
Motors	Stepper 1.8° , 2A ,12 V
Cutting bow	Width 170 mm, height 350 mm

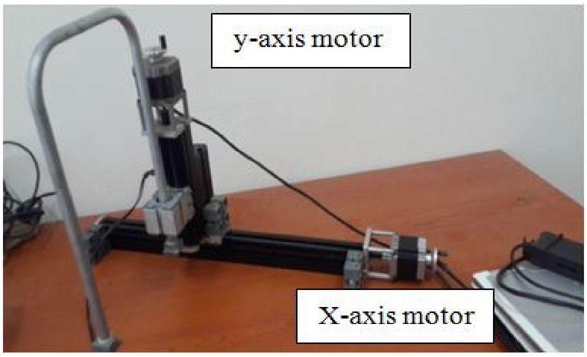

Fig. 3. The two axis of CNC.

The cutter consists of an elbow of aluminium insulated by small ceramic cylinders on both ends to avoid short circuit, and the wire of cut which is Nichrome (Nickel-Chromium alloy).

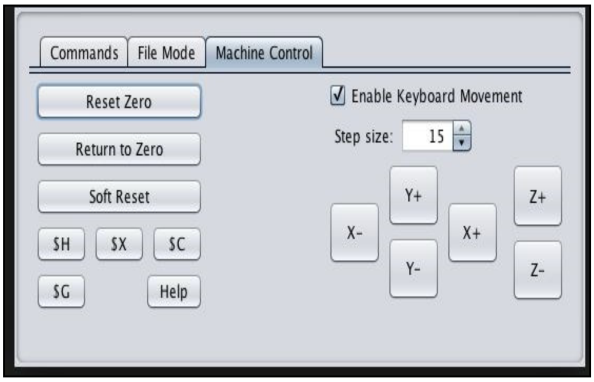

Fig. 4. screenshot of the Gcode universal.

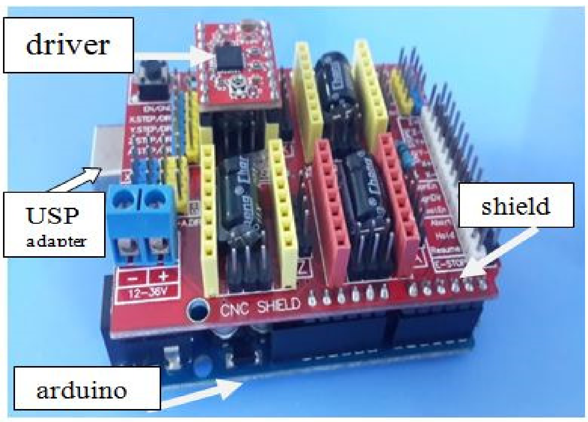

Fig. 5. Arduino and CNC shield.

3. Hot-Wire Process Parameters

3.1 Temperature of Wire

The five levels of temperature are (100,120,130,150,160) °C which can be adjusted by tunning the power supply. The infrared thermo camera FLIR T335 used to ensure the temperature of wire as shown in Figure 6.

Fig. 6. Infrared thermos camera FLIR T335.

3.2 Cutting Velocity of the Process:

The velocity levels are (200, 300, 400, 500, and 600) mm / min can be adjusted through the Universal G code sender software.

3.3 The Diameter of Wire

The available diameters in the market are:(0.3,0.4,0.5,0.7,0.8) mm.

3.4 The Density of Foams

The material of workpiece is XPS foam with different colours and densities (purple 0.037, yellow 0.032, blue0.029, pink 0.027 and white 0.01 g/cm^3) as shown in figure 7 to recognize each one according to the density.

Fig. 7. Foam colours.

4. Optimizing Parameter with MINITAB17 and Taguchi Technique

The MINITAB17 is statistical software using Taguchi method which is technique used to find the optimum values for the parameters and minimize the number of experiments that have to be done. Optimization of process parameters is done to make a great control to the process, It is effective way to improve quality of product at a relatively low cost. In this study Taguchi minimized the total experiments from 625 to 25 effective experiments in orthogonal array as shown in table 2. This orthogonal array has 25 rows and 4 columns, each columns represents specific process parameters while each row represents a trial condition [12,13].

Table 2,
the orthogonal array of Taguchi

No.	A code	B code	C code	D code
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	1	4	4	4
5	1	5	5	5
6	2	1	2	3
7	2	2	3	4
8	2	3	4	5
9	2	4	5	1
10	2	5	1	2
11	3	1	3	5
12	3	2	4	1
13	3	3	5	2
14	3	4	1	3
15	3	5	2	4
16	4	1	4	2
17	4	2	5	3
18	4	3	1	4
19	4	4	2	5
20	4	5	3	1
21	5	1	5	4
22	5	2	1	5
23	5	3	2	1
24	5	4	3	2
25	5	5	4	3

Table 3,
the orthogonal array of Taguchi uncoded

NO.	A (temp.)	B (diameter)	C (velocity)	D (density)
1	100	0.3	200	0.01
2	100	0.4	300	0.027
3	100	0.5	400	0.029
4	100	0.7	500	0.032
5	100	0.8	600	0.037
6	120	0.3	300	0.029
7	120	0.4	400	0.032
8	120	0.5	500	0.037
9	120	0.7	600	0.01
10	120	0.8	200	0.027
11	130	0.3	400	0.037
12	130	0.4	500	0.01
13	130	0.5	600	0.027
14	130	0.7	200	0.029
15	130	0.8	300	0.032
16	150	0.3	500	0.027
17	150	0.4	600	0.029
18	150	0.5	200	0.032
19	150	0.7	300	0.037
20	150	0.8	400	0.01
21	160	0.3	600	0.032
22	160	0.4	200	0.037
23	160	0.5	300	0.01
24	160	0.7	400	0.027
25	160	0.8	500	0.029

The foam cutting process can be outlined as the following steps, which describe the whole process done by the machine and then the results can be processed with the MINITAB software.

1. Fix the hotwire cutting CNC on the table
2. Fix the foam with in the proper place by fixtures.
3. Turn on the power to the WIRE, wait until reach to the required temperature of wire, that can be ensured by the infrared camera
4. Turn on the dc power supply of the shield, then give the order (Gcode of the required shape) to the motors to move, to cut by the arduino program (universal Gcode sender), with the velocity that given.

5. Wait until finishing the cut
6. Take the part to make measurements.
7. Find the material removal MR of the cutting pieces by comparing between the weight before and after the cutting process by using delicate balance.
8. Repeat all steps with changing the parameters according to the Tagauchi array of 25 experiments.
9. Enter the factors (inputs) and results(outputs) in the MINITAB program to find optimization.

5. Results and Discussion

The results have been analysed by using (MINIITAB17) in the following steps:

5.1 Signal to Noise Ratio (S/N)

The (S/N) ratio is defined as standard approach where the result used for the average of the result is run with the main parameter. The optimum with S/N ratio is studying, the main effect of the parameters and giving the optimum result which effect on the process. In the hotwire cutting process, the S/N ratio is used to measure the sensitivity of the quality surface characteristic with the parameters [14]. There are three categories of the quality characteristics: smaller is better, normal is better and larger is better, the aim of any experiment is always to determine the highest possible (S/N) for the result. In this study selecting the smaller is better which means the maximum response of the material removal with the smallest lost of material [15].

The mean squared deviation (MSD), (S/N) ratio and prediction are determined by the equations (smaller is better) below:

$$MSD=\left(\frac{1}{n}\sum_{i=1}^{n}(y^2)\right) \quad \dots (1)$$

$$(S/N)ratio=-\,10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}(y^2)\right) \quad \dots (2)$$

Where:

n: is the number of the trial

i: is trial number

The analysis of material removal is explained with the parameters by using (S/N) ratio, describes the quality of the surface in the hotwire cutting process. The results have been analysed by using S/N ratio to obtain the optimal level for each process parameter that has larger effect of the surface quality. The main effect of each parameter with four level on the S/N ratio and mean for material removal are calculated in the tables (3&4), the plot of the S/N ratio and mean is shown in the figure (8&9). Note: there are 4 experiments failed through cutting, so they neglected in all calculations.

Table 4,
The main effect of the S/N ratio for MR

s/n ratio for response					
level	**A**	**B**	**C**	**D**	**level**
1	59.21	48.98	46.19	44.26	1
2	41.81	45.20	46.35	44.26	2
3	43.37	51.21	45.38	38.99	3
4	45.29	37.76	44.05	45.25	4
5	45.99	45.84	45.63	39.96	5
Delta	17.39	13.46	2.30	17.17	Delta
Rank	1	3	4	2	Rank

S/N ratio optimization

Table 5,
The main effect of the mean for MR

Means for response				
level	**A**	**B**	**C**	**D**
1	0.001700	0.005620	0.007940	0.002860
2	0.008225	0.006120	0.007020	0.007160
3	0.008020	0.003767	0.007750	0.011575
4	0.007120	0.013275	0.007133	0.005975
5	0.007800	0.006975	0.005950	0.010233
Delta	0.006525	0.009508	0.001990	0.008715
Rank	3	1	4	2

Mean optimization

From the tables (3 and 4), the effect of each factor (Rank) can be seen which mean the effect degree of each factor on the MR. In addition, the optimal level of the parameters with MR is calculated according to the larger value of the mean and S/N ratio, so in this case the rank of optimal parameters which effected on the MR is: wire temperature (A), followed by density (D), then the wire diameter(B) and velocity of cut (C) , and It noticed that the optimal condition is : A1 , B3 , C2 , D4 for s/n ratio, and A2, B4 , C1 , D3 for means .

Figures (8&9) show the plots of SN ratio and Mean of the MR for the material.

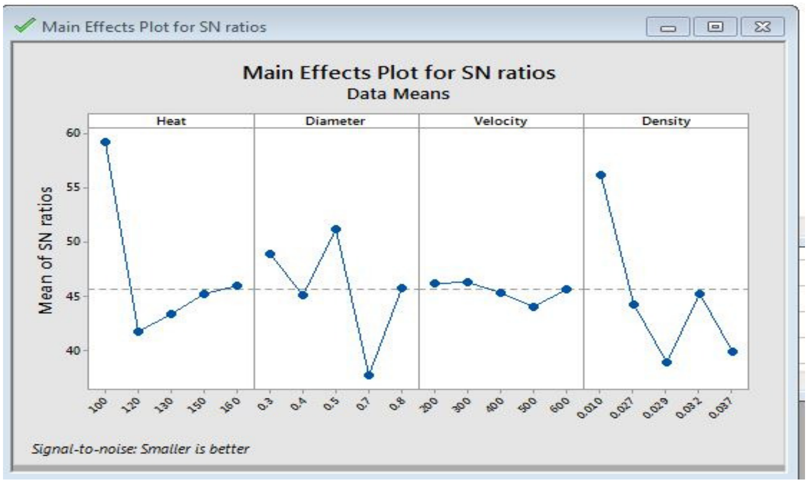

Fig. 8. Main effects plot S/N ratio plot for MR.

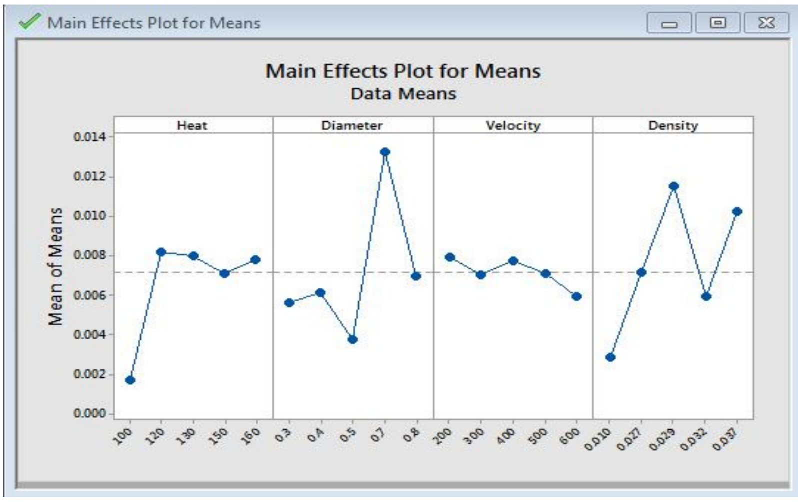

Fig. 9. Main effects plot of means for MR.

For this situation, we need to make a prediction. This can be used to predict the optimum level of S/N ratio and mean, then choosing the optimum level which depends on the large value of the S/N ratio [16] as shown in table 8.

Table 6,
The prediction of the mean and S/N ratio of MR

S/N ratio				**mean**			
A	B	C	D	A	B	C	D
1	3	2	4	2	4	1	3
S/N Ratio		Mean		S/N ratio		mean	
63.3489		-0.00066		38.4977		0.01147	

From the table 5 the optimum predict value for S/N ratio is 63.3489 which is the larger, that mean in the conditions of: A1(100 C), B3(0.5mm), C2(300mm/min), D4(0.032 gm/cm^{3}) the material removal is in the smallest removed amount which is the optimum result.

5.2 Analysis of the Variance (ANOVA)

The optimum of the work accomplished by determine the percentage of each parameter on the results of the experiments. The ANOVA is a statistical treatment analysis which is used for this purpose for the MR [16].

In this part, ANOVA is used to determine the influence of the parameters on the material removal as shown in the table 6.

Table 7,
ANOVA for MR

Source	Df	Adj SS	F-Value	P-Value	Contributed (%)
Temp. A	4	0.000033	0.65	0.655	3.4
Diameter B	4	0.000160	8.58	0.030	46.8
Velocity C	4	0.000039	1.04	0.484	5.5
Density D	4	0.000136	7.04	0.043	38.6
Error	4	0.000038			5.5
Total	20	0.000406			100

From table 6, it is noticed that the significant effect of the parameter is the diameter (B 46.8%) then the density (D 38.6%) followed by the velocity (C 5.5%), and temperature (A 3.4%) as shown in figure 10.

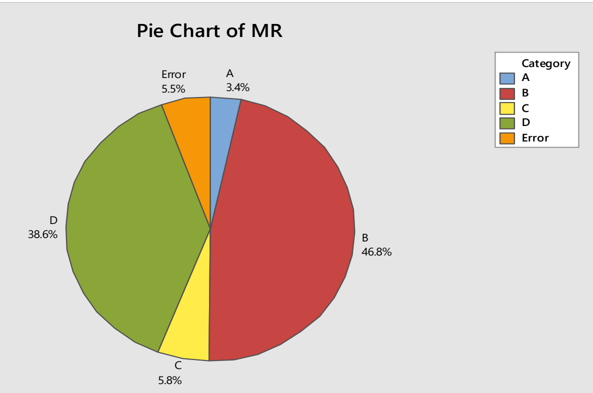

Fig. 10. The contributed percentage of the factor for MR.

5.3 Regression equations for MR

Regression is a statistical measure used to find and calculate the mathematical relationship between the independent variables and the dependant variables or in other word the input and output parameters which is linear [17].

The general form of multiple regression is:

$$y = a + b_1x_1 + b_2x_2 + b_3x_3 + \cdots + b_tx_t \quad \dots (3)$$

t = 1,2,3, ……n

While:

y: the output or the predicted variable

x: the input or the variable which is needed to find y value

a: constant

b: slope

By using MINITAB software, the regression equation for estimating the MR used to find the comparison between the experimentally and numerically results of them, that has been obtained as the following:

Y= - 0.00551+0.01008B + 0.2759 D ... (4)

Where:

B: the wire diameter

D: the density of foam

Y: Material Removal

6. Conclusions

From analysing the results of experiments, which they are physical and mechanical tests by using Minitab17 we obtained some conclusions and summarized as:

1. The Signal to Noise Ratio (S/N) for hotwire cutting process, found that: The optimum condition for MR are: the temperature is 100˚C, diameter of wire is 0.5 mm, velocity of cut is 300mm/min and density of foam is 0.032 gm/cm^3.
2. This research agreed with the previous researches, that the Diameter of wire B has larger percent of effect on the MR (46.8%), (because increasing the diameter cause to increase the MR), followed by the density of foam D (38.6%),(because of increasing the shear force), then the velocity of cutting C (5.8%), and temperature of wire A (3.4%) , because the melting of materials. Fig. 10 show the plot of the material that, increasing the diameter cause to increase MR.

7. Aknowledgment

Thanks a lot to God who helped me and gave me the strength to complete this research.

I would like to offer my thanks and appreciation to my supervisors al-Khwarizmi College of Engineering for continual inspiration and gave me all support during the research period.

Thanks to my family that I always find beside me to give full support in my life.

Special thanks are due to my husband who was the source of my power in the Moments of weakness.

Finally, I would like to express my thanks to my friends and everyone who gave me any type of assistance throughout the course of research

List of Abbreviations

ANOVA	Analysis of Variance
CNC	Computer Numerical Control
EPS	Expanded Polystyrene
MR	Material Removal
OA	Orthogonal Array
Ra	Surface roughness
SMPS	Switched-Mode Power Supply
S/N	Signal to Noise Ratio
XPS	Extruded Polystyrene

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إيجاد المثالية لمتغيرات عملية القطع بالسلك الحراري لتحسين خواص فوم البولسترين

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الخلاصة

القطع بالسلك الكهربائي هو احدى الطرائق غير التقليدية الميكانيكية الحرارية لقطع البوليمر عادة اما الفوم التمددي او الفوم الانبثاقي في الإنتاج ذو الحجم القليل. الدراسة والتحليل لعوامل القطع بالسلك الحراري تؤدي الدور المهم في تحسين جودة العملية ودقتها للمنتوجات. التأثيرات على السطح تم ايجادها باستخدام تصميم التجارب العملية طبقا الى مصفوفة تا كوشي. في هذه الدراسة تم استخدام أربعة متغيرات مع خمسة مستويات لكل متغير (حرارة السلك °C ١٦٠، ١٥٠، ١٣٠، ١٢٠، ١٠٠) و(قطرالسلك mm 0.3,0.4,0.5,0.7,0.8) و(سرعه القطع mm/min ٢٠٠ ٣٠٠ ٤٠٠ ٥٠٠ ٦٠٠) و(كثافة g/cm^3 0.01,0.027,0.029,0.032,0.037) وتم استخدام برنامج MINITAB 17 لايجاد المثالية لظروف القطع وكانت نتيجتها على وفق النحو الاتي:

MR : 100˚C, 0.5 mm, 300mm/min, 0.032 g/cm^3 وكذلك نسبه تأثير كل عامل على العملية تم ايجادها.