Military Technical College
Cairo, Egypt

12th International Conference
on Applied Mechanics and
Mechanical Engineering (AMME)

STUDYING THE PARAMETERS INFLUENCING THE ACCURACY OF ELECTRON BEAM DRILLED HOLES

ELNAGGAR[*] , W. M., KOHAIL[**] ,A. M. and MOUGHITH[*] .W. S.

ABSTRACT

Electron beam drilling has been widely used in industry. The drilling process is performed when the electron beam is focused with enough energy to melt and vaporize the drilled substrate. The present work introduce the study of the influence of different beam parameters as beam current, focusing current and pulse frequency on the accuracy of the drilled holes in low carbon steel specimens. High speed machining experiments with deflection coil are performed. The produced holes accuracy is evaluated mainly by conicity and circularity.

KEY WORDS

Electron, Beam, and Drilling

NOMENCLATURE

D_e	Exit diameter
D_i	Inlet diameter
EB	Electron beam
EBM	Electron beam machining
ECM	Electro chemical machining
EDM	Electric discharge machining
f	Pulse frequency
Ib	Beam current
If	Focus current
LBM	Laser beam machining
SEM	Scanning electron microscope
T	Hole tapering
O_i	Ovality index

* Egyptian Armed Forces
** Associate professor, Faculty of Technology, Workers University, Cairo, Egypt.

1. INTRODUCTION

As a machining process, Electron Beam Machining (EBM) is often mentioned along with Laser Beam Machining (LBM), Electrical Discharge Machining (EDM) and Electro Chemical Machining (ECM). These techniques are called nontraditional techniques which are used when the requirements exceed mechanical machining and drilling capabilities, or because they have overriding cost advantages. Compared to other hole drilling techniques, the electron beam process has unique features that give it special capabilities for hole drilling over a wide variety of applications such as small hole diameters, high machining rate and low heat affected zone [1].

The first electron beam machine was a drilling machine which was used for drilling holes in jewel bearings of watches. The idea originated with Manfred von Ardenne in 1938 but it wasn't until it was developed by the physicist Karl-Heinz Steigerwald at Carl Zeiss in the early" fifties"[2].

The machine utilizes the kinetic energy of accelerated electrons and the facility for focusing them to a high power density in vacuum by electromagnetic focusing and deflection coils. This properly enables materials to be melted and vaporized [3]. In non-contact machining , for example; electron beam machining (EBM) , laser machining or electric discharge machining , the dimension of hole or grove can be easily varied by energy supplied to the workpiece. Thus, these non-contact machining is not affected by the abrasion of tools. Therefore, the authors have investigated the machining of low carbon steel with an electron beam, as form of non-contact machining [4].

As the beam penetrates the material, the temperature rises initially at a rate of over 1,000°C per microsecond, causing localized melting and vaporization. As this heating continues, a high vapor pressure in the center of the cavity presses the molten metal radically outward and upward, allowing the beam to penetrate through the vapor and rapidly deepen the cavity. Backing material with special properties is placed behind the workpiece. When the beam drills the hole and enters the backing material, additional high vapor pressure is generated, ejecting the molten metal upward and leaving a clean hole with minimum recast, as shown in Figure 1. [1].

2. EXPERIMENTAL SETUP

The used machine in this experiment is Electron beam welding/cutting machine SEO TECH-60/1.1. The experiments used to investigate the influence of the different parameters affecting the electron beam characteristics. The selected parameters chosen during this study are the electron beam current, focusing current and pulse frequency. These parameters affect the characteristics of the drilled holes using the electron beam machining. The drilled hole characteristics are the hole inlet and exit diameters, circularity and tapering The drilled hole dimensions were measured using tool-maker microscope. Table1 shows the conditions of the presented work experiments.

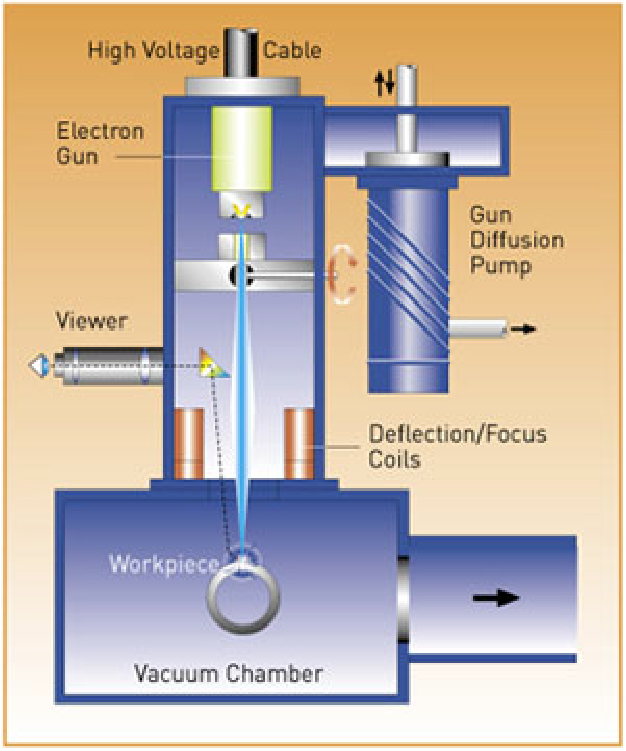

Fig. 1 The basic concepts of electron beam machining [1]

Table 1. Experimental setup Conditions

Workpiece material	Low Carbon steel sheet (3 mm) with composition (C0.08% , Si 0.08% and Fe 99.51%) and full annealed
Accelerating voltage	60kv
Beam current (I_b)	(5, 6, 7, 8, 9, 10, 11, 12) mA
Focusing current (I_f)	(855, 860, 865,) mA
Pulse frequency (f)	(12, 20, 28, 36, 44) Hz
Total numbers of runs during the experiments (N)	120 runs of the all possible combinations of the investigated parameters.

3. RESULTS AND DISCUSSION

A statistical package (MINITAB software) was used to investigate the process parameters (the beam current, focusing current and plus frequency) to obtain their effects on the hole characteristics which were selected as inlet diameter (D_i), exit diameter (D_e), hole tapering (T) and circularity represented by ovality index (O_i). Then, using a multiple regression analysis, a third order mathematical model relating the process parameters and the drilled hole characteristics was developed.

The following subsections illustrate the effect of process parameters on the hole characteristics.

3.1 The Influence of Beam Parameters on the Hole Inlet Diameter

The analysis of variance for the process parameters was developed to investigate their significance on the hole inlet diameter as shown in table 2 revealing that all the selected parameters were significant but the focusing current was the most significant since its F-value is the greatest among the others.
The main effect of the plus frequency, focusing current and beam current was examined as shown in figures 2, 3 and 4.

Table 2. Analysis of variance of the process parameter vs. the inlet hole diameter

Source	DF	SS	MS	F-value	P-value
f	4	1.00532	0.12611	23.42	0.000
I_f	2	0.50443	0.50266	93.35	0.000
I_b	7	1.39257	0.19894	36.95	0.000
Error	106	0.57075	0.00538		
Total	119	3.47307			

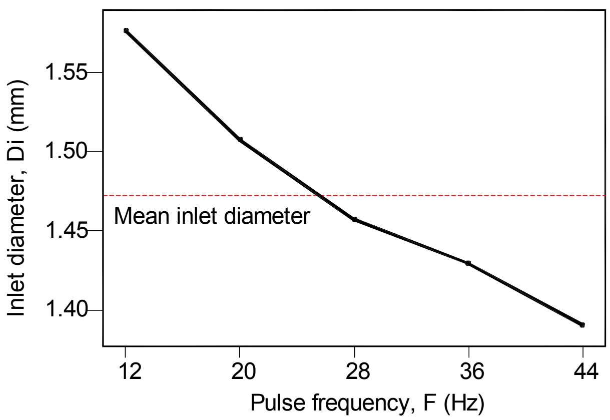

Fig. 2 Main effect plot of pulse frequency on the inlet diameter of the hole

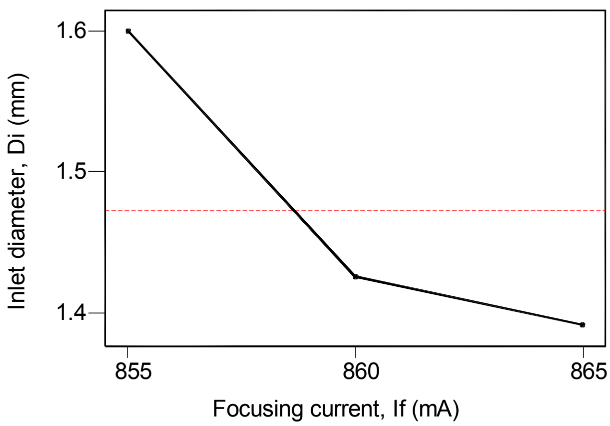

Fig. 3 Main effect plot of focusing current on the inlet diameter of the hole

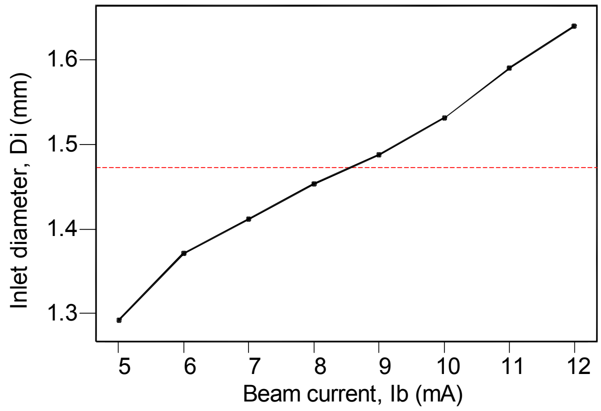

Fig. 4 Main effect plot of beam current on the inlet diameter of the hole

The increasing in pulse frequency leads to decrease the duration time of applied beam current (On-time) and decrease the Off-time used to evacuate the removed material i.e. evacuate a small amount of the molten material [5]. Then increasing in frequency decreases the inlet diameter as shown in Figure 2.

The focusing current controls the position of the focal point of the beam from the machined surface so that by increasing the focusing current the focal point moves from the electron beam gun direction towards the top of the machined surface leading to decreasing the beam diameter and consequently the inlet hole diameter decreases as shown in Figure 5.

Figure 4 shows that the increasing in beam current increases the inlet diameter of the drilled hole since the increasing in the energy supplied to the workpiece material. Figure 6 shows that the focal point of the electron beam can be obtained at the surface of the sheet at focusing current 865 mA where there is no change in the value of the inlet diameter compared with its value at the previous focusing current 860 mA.

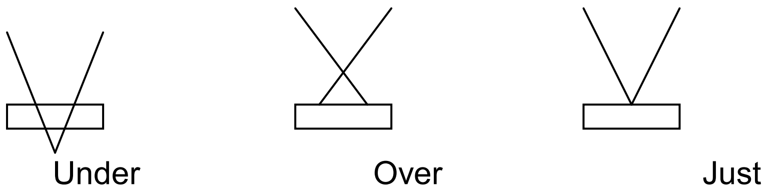

Fig. 5 Different focal point position with respect to the machined surface

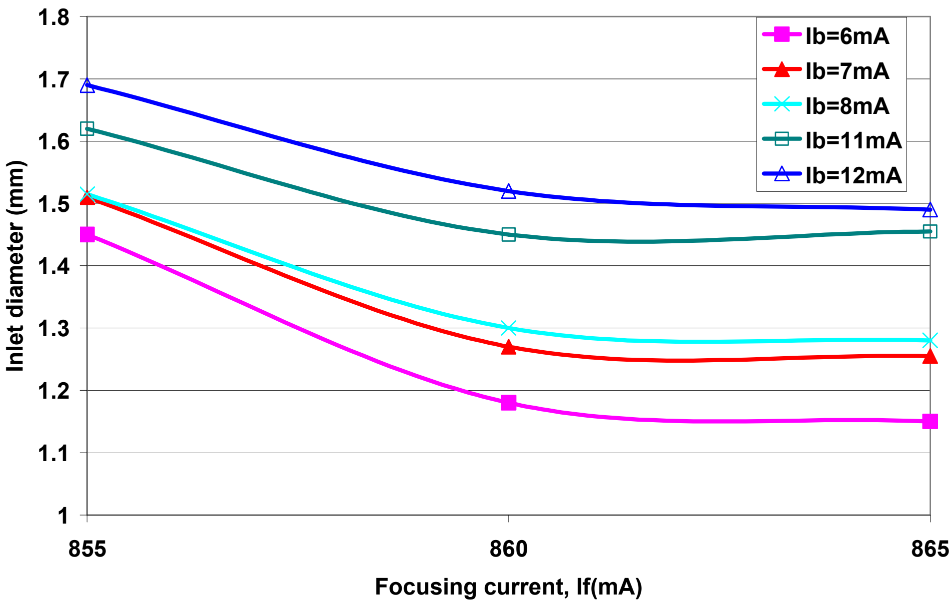

Fig. 6 The variation in inlet diameter with focusing current at different beam currents

A mathematical model representing the relationship between the selected process parameters and the inlet hole diameter can be conducted using the multiple regression analysis as shown below.

$$D_i = 2140 - 0.822\,F - 4.91\,I_f - 6.43\,I_b + 0.000931\,F\,I_f + 0.155\,F\,I_b + 0.00778\,I_f\,I_b + 0.000498\,f^{2} - 0.0262\,I_b^{2} + 0.00281\,I_f^{2} - 0.000005\,F^{3} + 0.00102\,I_b^{3} - 0.000180\,f\,I_f\,I_b \quad (1)$$

The coefficient of multiple determination R^2 equals 0.9 and the adjusted R^2 statistic R^2_{adj} is 0.89. Since these two values are close there is no significant parameters can be added to the model. The measured and predicted drilled hole inlet diameter at some runs are plotted in figure 7, revealing that the predicted and measured results almost match.

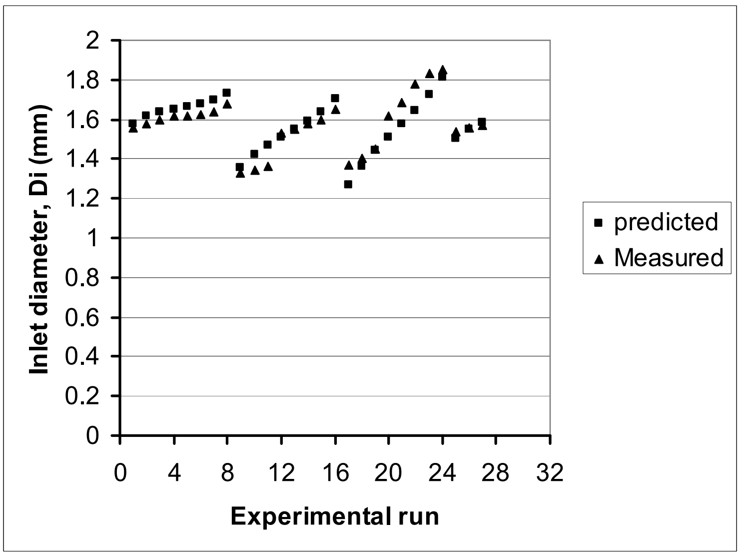

Fig. 7 Measured and predicted drilled hole inlet diameter, Di

3.2 The Influence of Beam Parameters on the Hole Exit Diameter

Table 3, shows the analysis of variance for the process parameters to investigate their significance on the hole exit diameter. This table shows that all the selected parameters were significant but the focusing current is still the most significant since its F-value is the greatest among the others. The main effect of the plus frequency, focusing current and beam current are shown in figures 8, 9 and 10.
As mentioned in the effect of the selected process parameters on the inlet diameter, these parameters affect on the exit diameter with the same manner. The mathematical model representing the relationship between these parameters and the exit diameter is given below.

$$D_e = 821 - 0.632\,F - 1.87\,I_f - 1.31\,I_b + 0.000725\,F\,I_f + 0.0753\,F\,I_b + 0.00157\,I_f\,I_b + 0.000063\,F^2 + 0.0025\,I_b^2 + 0.00107\,I_f^2 - 0.000001\,F^3 - 0.000215\,I_b^3 - 0.000087\,F\,I_f\,I_b \quad (2)$$

Table 3. Analysis of variance of the process parameter vs. the exit hole diameter

Source	DF	SS	MS	F-value	P-value
F	4	0.15710	0.03928	20.48	0.000
I_f	2	0.94789	0.47394	247.08	0.000
I_b	7	1.76067	0.25152	131.12	0.000
Error	106	0.20333	0.00192		
Total	119	3.06899			

The R^2 and R^2_{ad} coefficients were obtained 0.96 and 0.95, respectively. Since these two values are close and near to unit, the mathematical model is robust and significant. Also, the measured and predicted drilled hole exit diameter at some runs are plotted in figure 11 revealing that the predicted and measured results are matched.

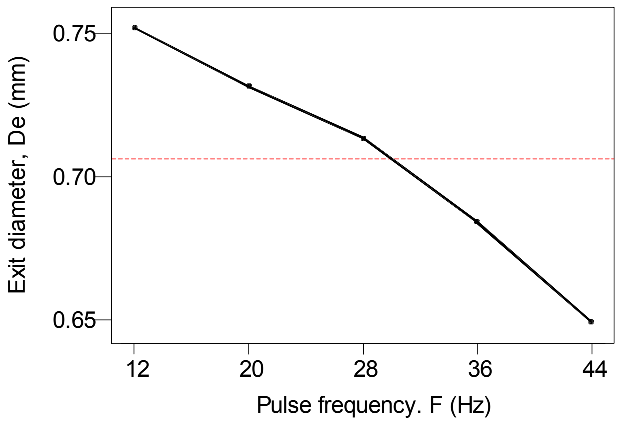

Fig. 8 Main effect plot of pulse frequency on the exit diameter of the hole

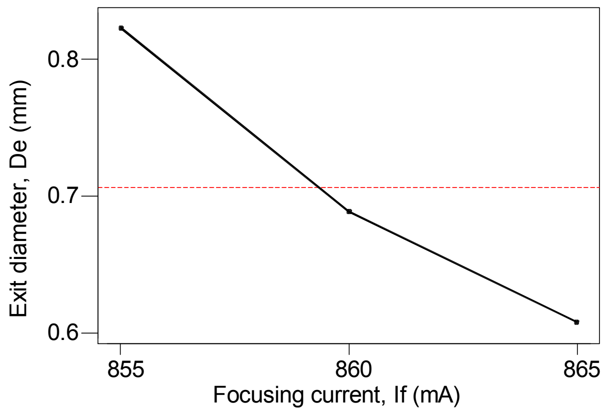

Fig. 9 Main effect plot of focusing current on the exit diameter of the hole

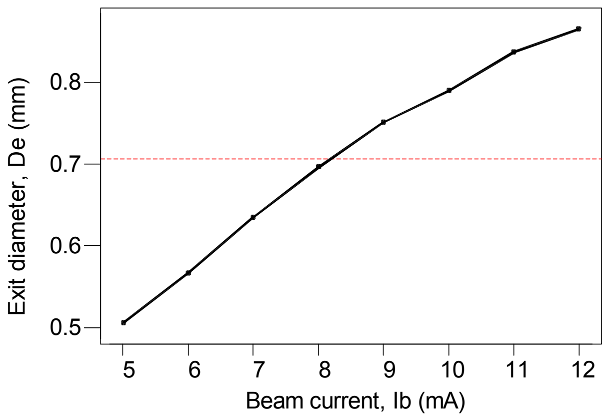

Fig. 10 Main effect plot of beam current on the exit diameter of the hole

3.3 The Influence of Beam Parameters on the Hole Tapering

The hole tapering is represented by the following relationship [6]:

$$\theta = tan^{-1}\left(\frac{D_i - D_e}{2L}\right)$$

Where:

L hole depth (sheet thickness)

θ inner angle of the cone shape

D_i inlet diameter

D_e exit diameter

Table 4 illustrates the analysis of variance for the process parameters to investigate their significance on the hole tapering. Also, it reveals that the most significant parameter is the pulse frequency while the beam current is not significant (P-value = 0.342).

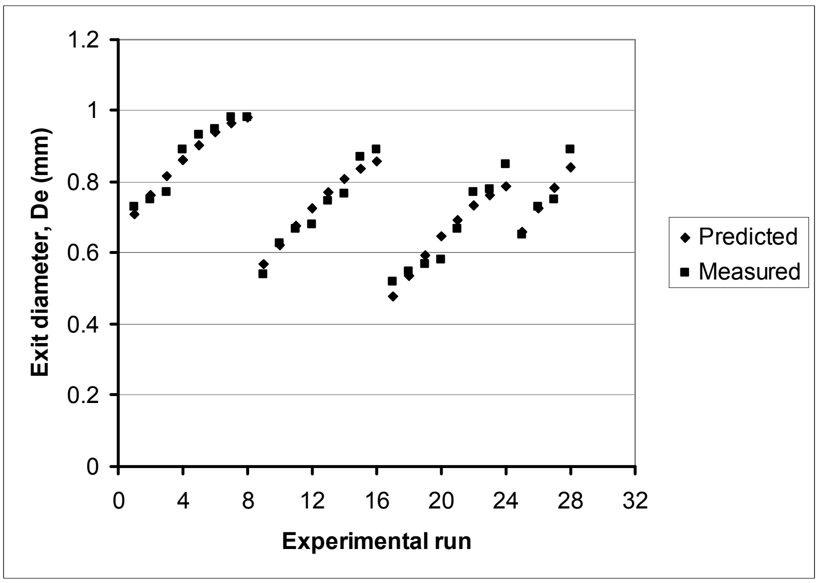

Fig. 11 Measured and predicted drilled hole exit diameter, De

Figure 12 shows the main effect of pulse frequency on the hole tapering and illustrates a decreasing in the hole tapering by increasing the pulse frequency. Figure 13 shows the main effect of the beam current on the hole tapering and reveals that the hole tapering is decreased by increasing the beam current until 9 mA and then increased. Also figures 12 and 13 reveal that the mean value of the hole tapering is 7.27 deg. approximately within the range of the selected process parameters. Figure 14 shows an interaction between the beam current and focusing current on their effect on hole tapering and reveals that the lower beam current the better hole tapering.

Table 4 Analysis of variance of the process parameter vs. the hole tapering

Source	DF	SS	MS	F-value	P-value
F	4	10.7941	2.6985	4.20	0.003
I_f	2	4.5111	2.2555	3.51	0.033
I_b	7	5.1400	0.7343	1.14	0.342
Error	106	68.0401	0.6419		
Total	119	88.4852			

3.4 The Influence of Beam Parameters on the Hole Circularity

The hole circularity was represented by measuring the ovality index which was obtained by the difference between the major and minor inlet diameter using a toolmaker microscope. Table 5 shows the analysis of variance of the selected process parameters affecting the ovality index. The beam current is the most significant parameter affecting the ovality index.

Figures 15, 16 and 17 show the main effect of the pulse frequency, focusing current and beam current on the ovality index representing the hole circularity.

Figure 15 shows that the circularity can be improved by increasing all the pulse frequency until 36 Hz and also illustrates that the mean value of the ovality index is 0.12 mm. Figure 17 shows an improvement in ovality index by increasing the beam current from 5 mA to 12 mA.

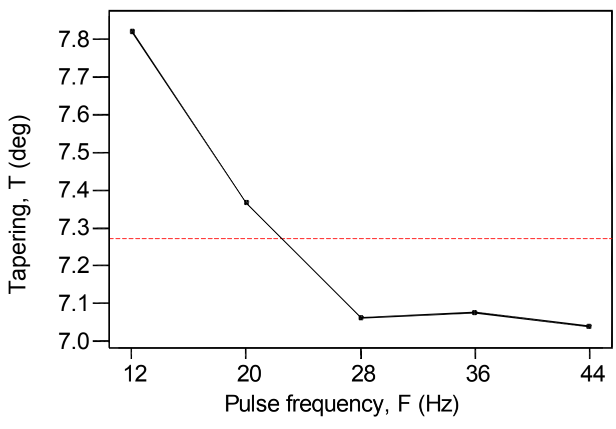

Fig. 12 Main effect plot of pulse frequency on the hole tapering

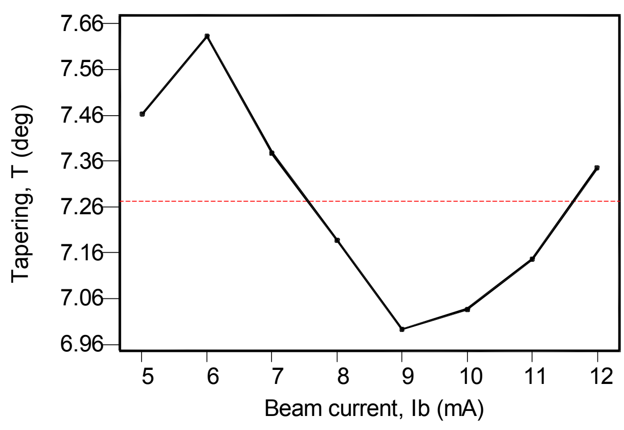

Fig. 13 Main effect plot of beam current on the hole tapering

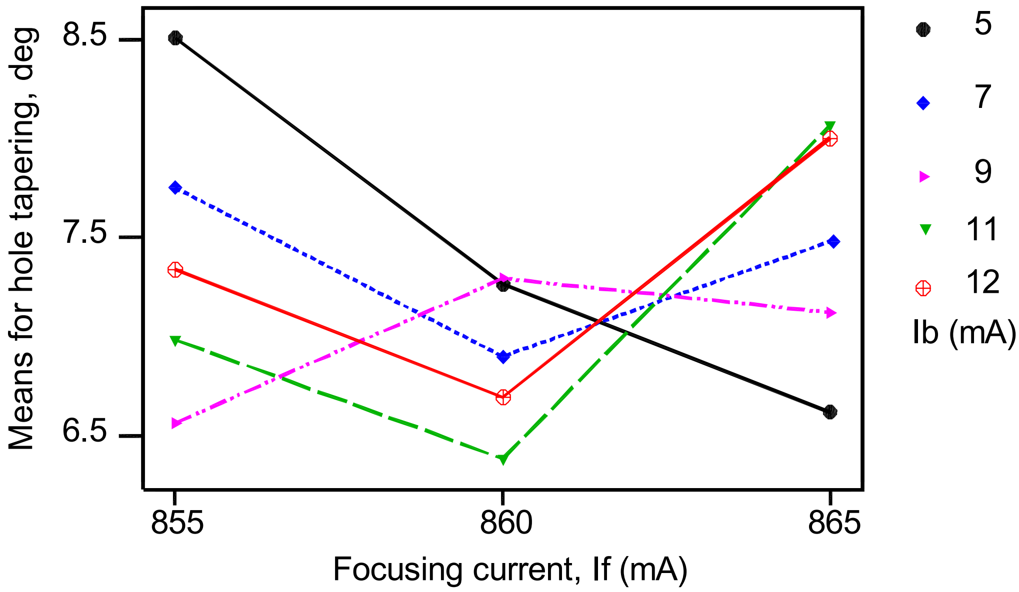

Fig. 14 Interaction plot for data means for hole tapering

Table 5 Analysis of variance of the process parameter vs. the ovality index

Source	DF	SS	MS	F-value	P-value
F	4	0.086149	0.021537	32.85	0.000
I_f	2	0.013888	.006944	10.59	0.000
I_b	7	0.228986	0.032712	49.90	0.000
Error	106	0.069486	0.000656		
Total	119	0.398509			

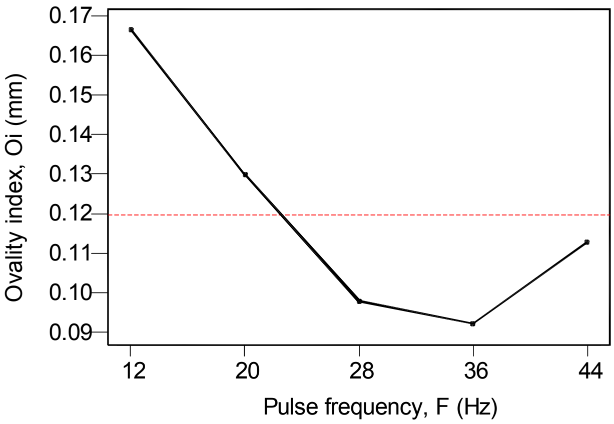

Fig. 15 Main effect plot of pulse frequency on the hole ovality index

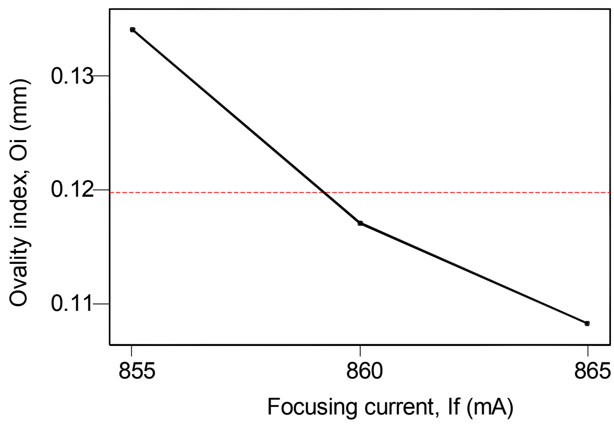

Fig. 16 Main effect plot of focusing current on the hole ovality index

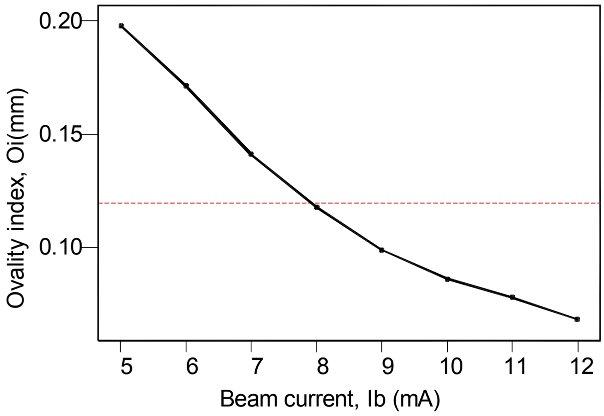

Fig. 17 Main effect plot of beam current on the exit diameter of the hole

3.4 Contour Plot for the Hole Inlet Diameter

The influence of the pulse frequency and beam current on the hole inlet diameter (equation 1) can be represented graphically using a contour plot as shown in figure 18. This plot can be used to obtain the setting values of the pulse frequency and beam current corresponding to the required inlet diameter.

4. CONCLUSIONS

The hole characteristics of a low carbon steel sheet with electron beam machining have been discussed in the present work. The results show that:

- The investigated parameters of the electron beam machining, pulse frequency, beam current and focusing current are highly affecting the hole characteristics.
- To obtain high accuracy of drilled holes using the electron beam machining, the focal point of the beam should be on the machined surface by changing the focusing current, where no changing in the hole inlet diameter (at the present work is equal 865 mA). Then the pulse frequency and beam current can be used as cutting conditions for the electron beam machining used in drilling process.
- The contour plot is very useful to select the different beam parameters in order to obtain the hole inlet diameter with acceptable accuracy.
- As shown in Figure 13 and 16, the best working beam current range is ranged from 5 to9 mA which obtains a small tapering and conicity.
- Figure 12 and 15 show that the best working condition for the pulse frequency is ranged from 28 – 44 Hz as shown in figure 18 (the hatched area).

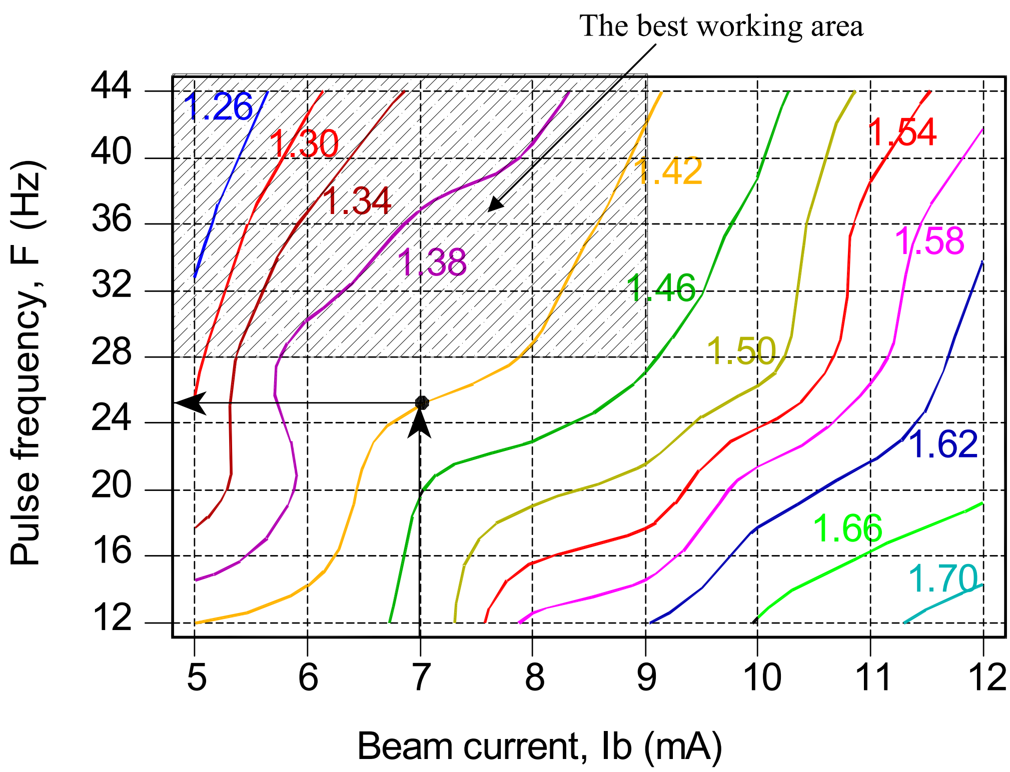

Figure 18 contour plot for the hole inlet diameter

REFERENCES

[1] ACCELERON INC 21 Lordship Road, East Granby, CT 06026

[2] H. Smith, Introduction to Electron Beam Technology, J. Wiley and Sons, N. Y., 1962

[3] ASM Hand book, Joseph R. Davis and S.R. Lampman and T.B. Zorc, ninth edition Ronald W. Schneider, MG Industries, Systems Division, copyright 1989 by ASM international

[4] Beam Defocus Effect in Electron Beam Machining of Green Ceramic Sheet. Kenichiro Horio, Takao Terabayashi; Production Engineering Research Laboratory, Hitachi ltd. Submitted by Norio Taniguchi (1), Received on February 26, 1987-Accepted by the Editorial Committee

[5] Instruction Manual for Model 5 MHz Function generator

[6] Metrology for Engineers, By J. F. W. GALYER and C. R. SHOTBOLT, Fifth Edition, Cassell Publisher Ltd 1990