Experimental Investigation of process & response parameters in Micro Drilling using Scanning Electron Microscope (SEM)

Anil Jindal

M.Tech. Student, Thapar University, Patiala.

ABSTRACT

Micro drilled holes are utilized in many of today's fabrication processes. Precision production processes in industries are trending toward the use of smaller holes with higher aspect ratios, and higher speed operation for micro deep hole drilling. However, undesirable characteristics related to micro drilling such as small signal-to-noise ratios, wandering drill motion and excessive cutting forces can be observed when cutting depth increases. In the experimental study, the application of the DOE (Design of Experiment) method and Scanning Electron Microscope (SEM) is utilized. In particular, it is found in this study that the feed rate is the most important factor for micro drilling process.

Keywords: Micro drilling process, Poly methyl methacrylate (PMMA), Feed rate, DOE (Design of Experiment), Scanning Electron Microscope (SEM).

Introduction

Drilling is one of the basic machining process of making holes and it is essentially for manufacturing industry like Aerospace industry, watch manufacturing industry, Automobile industry, medical industries and semiconductors. Especially Drilling is necessary in industries for assembly related to mechanical fasteners. It is reported that around 55000 holes are drilled as a complete single unit production of the Air bus A350 aircraft. Micro drilling of metals is increasingly required as products become smaller and more highly functional. With increasing demand for precise micro component production, the importance of micro-hole drilling processes is increasing rapidly. Because of the requirement of deeper and smaller holes required in the above said industries, it is required for micro drilling process technologies to achieve higher accuracy and higher productivity. There are several conventional and non conventional manufacturing processes by which micro drilling can be possible. Micro-drilling using laser beam, Electrons beam and Electric discharge methods and also electrolytic polishing, electrochemical machining has been frequently used by industries and for experimental researches.

However, for general applications, conventional micro drilling process is preferred due to their higher economical benefits than other processes and also it has highly productivity than other non conventional drilling processes. Polymethyl methacrylate (PMMA) is an important amorphous thermoplastic with desirable properties, including clarity (the transparency is close to the ultraviolet region and also the infrared), chemical resistance, good mould ability, protection against ultraviolet radiation, good weather ability, high strength, and dimensional stability. Hence, Poly methyl methacrylate (PMMA) promises fruitful development for applications in the aerospace sector due to its high strength, low density and thermal stability. Conventional mechanical drilling of PMMA has to face increasing physical limitation when hole diameter is decreased.

To realize a more efficient micro-drilling process, a step-feed process is required instead of the one-pass drilling method. The step-feed process repeats drill feeding forward and backward with a certain number of steps, as shown in Figure 1. This provides better discharge of chips and heat, longer tool life, and more accurate drilling results. With increased step-feeding frequency, it is possible to achieve more enhanced chip and heat discharge; however, the total processing time increases consequently. Conversely, the total processing time can be reduced by decreasing the step-feeding frequency, but chip and heat discharge is degraded. Thus, it is necessary to determine the optimal drilling conditions based on reliable experimental results to improve the productivity in the micro drilling processes.

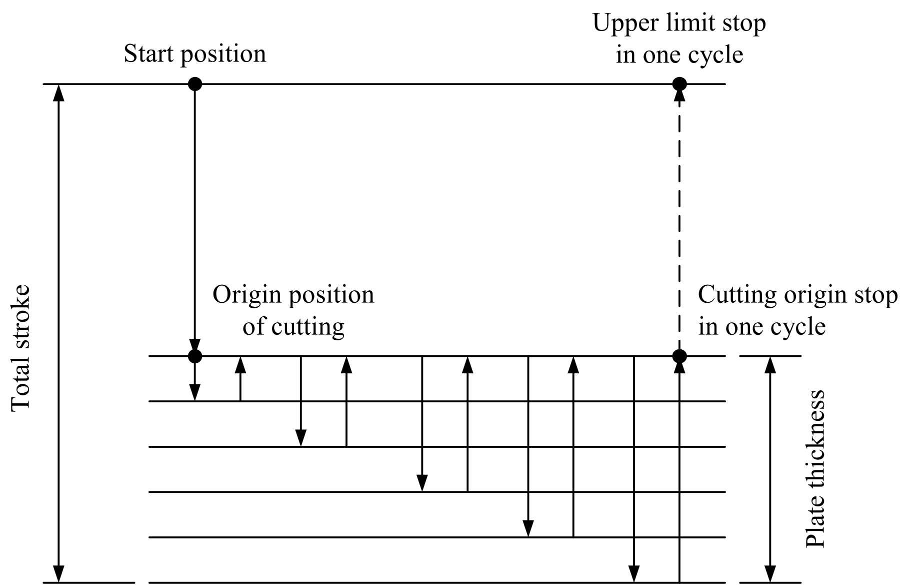

Fig. 1. Diagram of step feeding micro drilling method

2. Experimental Setup

In the experimental studies, a micro drilling system employing a high speed air spindle is used. The drilling process is divided into a certain number of steps and the drill is fed into the workpiece and retracted repetitively. This allows avoiding micro drill fracture problems and providing enhanced chip and heat discharge. Figure 2 illustrates the configuration of the experimental system used in this study, and the specifications of the micro drilling system are provided in Table 1. In order to monitor the states of the workpieces and the drilling processes in real time, as well as to measure the drilling thrusts, a microscope with a built-in monitoring system and a measuring instrument for cutting force are established, respectively. The specifications of these systems are given in Table 2.

2.1. Tool and Material:

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In the experiment, Poly methyl methacrylate (PMMA) strip which is having dimensions of 85x20x3mm (length x breadth x thickness) was used as work- piece material. The HSS Straight shank twist drills and tools were used in this experiment. The drill bit is of 4 mm diameter and 1180 point angle and flute length is 20 mm. The Quartz 4 component Dynamometer (type 9272A, Kistler made) along with Multi Channel charge Amplifier Type 5070 A was used for thrust force measurement. The Circularity and Burr Size were measured using SEM Pictures.

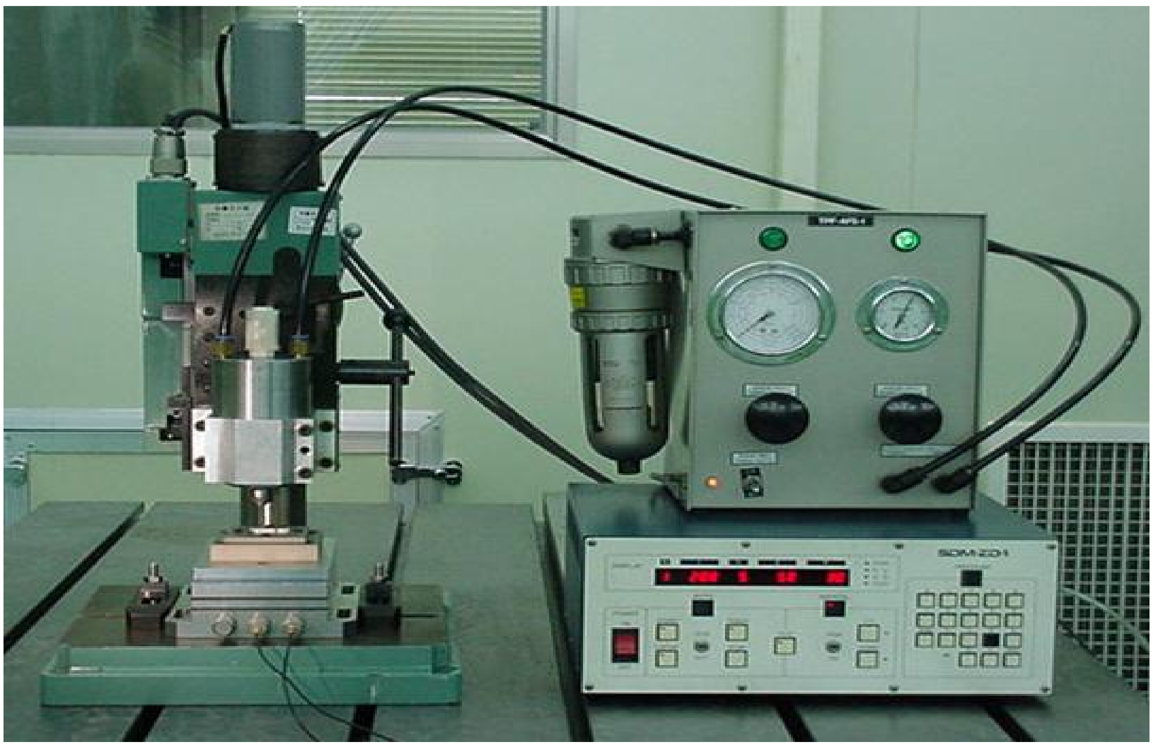

Fig. 2. Experimental setup for micro drilling

2.2. TAGUCHI METHOD

Taguchi Analysis is one of the efficient tools for manufacturing design. Taguchi's method shows an integration of Design of Experiments with optimizing of parameters to get the required result. Taguchi's Signal to noise ratios (S/N ratio) which are logarithm functions of required output serve as intended functions for optimization. This technique has been continuously used by researchers to analyse data to get an optimal solution. In order to finding out the optimum solution in a manufacturing design, taguchi method utilizes signal to noise ratio. The advantage of taking S/N ratio is that it takes into account both mean and variance. It may be defined as the ratio of mean value (Signal) to that of standard deviation (Noise).

The objective function in this work is to maximize the S/N ratio and is defined according to taguchi method as:

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$$\frac{S}{N}\text{Ratio} = -10\log\left[\frac{1}{n}\sum_{1}^{n}\frac{1}{Yi^2}\right]$$

Where Yi represents the judging parameter through which optimum set is to be found out.

Table 1 Specifications of experimental micro drilling system

Drilling ability	0.05 ~ 2.0(Φ) mm
Tool speed (Revolution)	50,000(Max.) rpm
Torque	500 gr-cm
Air pressure (Bearing)	5 ~ 6 kg_f/cm^2
Step feed rate	0.01 ~ 99.99 mm
Total stroke	75 mm
Height to collets	From table surface 30 ~ 200 mm
Size of machine body	300 × 350 × 680 mm
Weight	35 kg

Table 2. Measuring instrument of experiment for cutting force

Work-piece	Poly methyl methacrylate strip (85x20x3mm)
Dynamometer	Kistler Co. (9272A)
Amplifier	Kistler Co. (5070A)
Feed(mm/rev)	0.14,0.22,0.34

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Spindle Speed(rpm)	90,140,320

The spindle speeds used in the experiment were 90, 140 and 320 rpm. And the three feeds were selected as 0.14, 0.22, 0.34 mm/rev. In this experiment, two machining parameters having 3 levels each was taken as input parameter and thrust force was measured. Circularity and Burr size was measured using Scanning Electron microscope.

3. Experimentation

In the experimentation, Micro drilling of PMMA Sheet with less burr size and better accuracy is a challenge to manufacturing industries. Various process parameters affecting this can be feed, Spindle speed, tool diameter, Drill Bit material, drill geometry and cutting conditions. In the present work Feed and spindle speed are taken as process parameters.

Table 3. Experimental Data (Design of Experiments – DOE)

Standard Order	Run Order	Feed (A)	Speed(B)	Thrust Force(N)	Circularity (µm)	Burr Size (µm)
6	1.	2	3	29	20	160
5	2.	2	2	27	20	200
3	3.	1	3	17	20	70
7	4.	3	1	45	40	170
4	5.	2	1	27	10	100
1	6.	1	1	19	20	130
8	7.	3	2	50	20	90
2	8.	1	2	19	40	130
9	9.	3	3	45	80	280

Parameters related to thrust force was measured using Dynamometer and Circularity error and Burr Size were measured with the use of Scanning Electron Microscope. The micro drill holes are shown in the Fig. 3 for different combinations of drilling feed and spindle speed. Experimental data has been provided in table 3. All these data have been used to evaluate the optimal parameter combination to achieve desired micro drilling process.

For the analysis of data acquired through DOE, Taguchi method is applied for gathering required data by using an orthogonal array and investigating the S/N ratio (Signal-to-Noise ratio) derived from these data. In the approaches, characteristics of loss functions are usually classified into “Smaller the Better Characteristics”, “Larger the Better Characteristics” and “Nominal the Best Characteristics”. In these experiments, “Smaller the Better Characteristics” are taken into account in order to determine drilling conditions for producing minimal drilling thrust. Taking into account the interactions of A x B and A x C, the factors are assigned and the experiments are carried out.

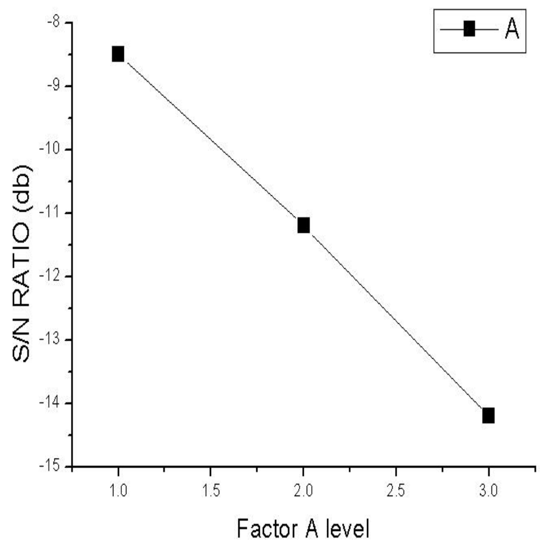

Fig. 3. S/N Ratio response graph

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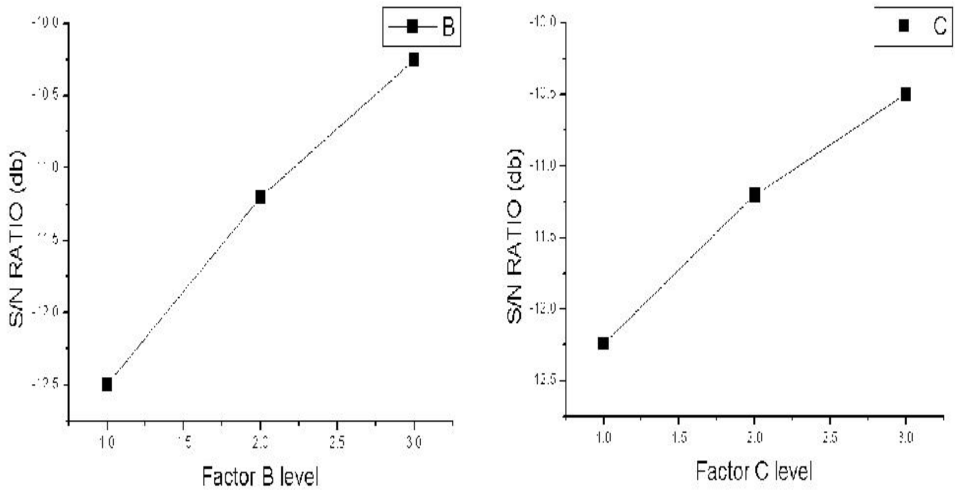

Fig. 4. S/N Ratio response graph

The process of ignoring a factor if it is deemed insignificant, called pooling, is done by combining the measure of influence of the factor with that of the error term. Finally, on the bases of the S/N ratio graphs and ANOVA, it can be declared that A1, B3, and C3 correspond to the factors producing minimal drilling thrusts and there are no interactions between A*B and A*C. Figure 6 shows the actual micro drilling process and a 200μm hole drilled based on the applied methods. Design of Experiments that has been selected using Statistical software (STATISTICA) as per full factorial design.

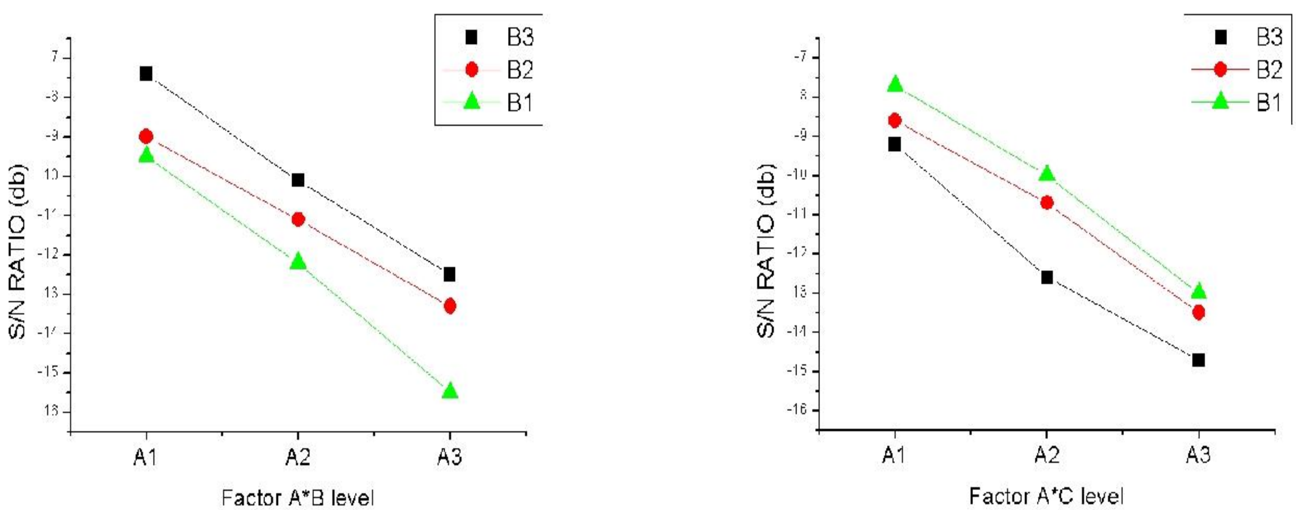

Fig. 5. S/N Ratio response graph

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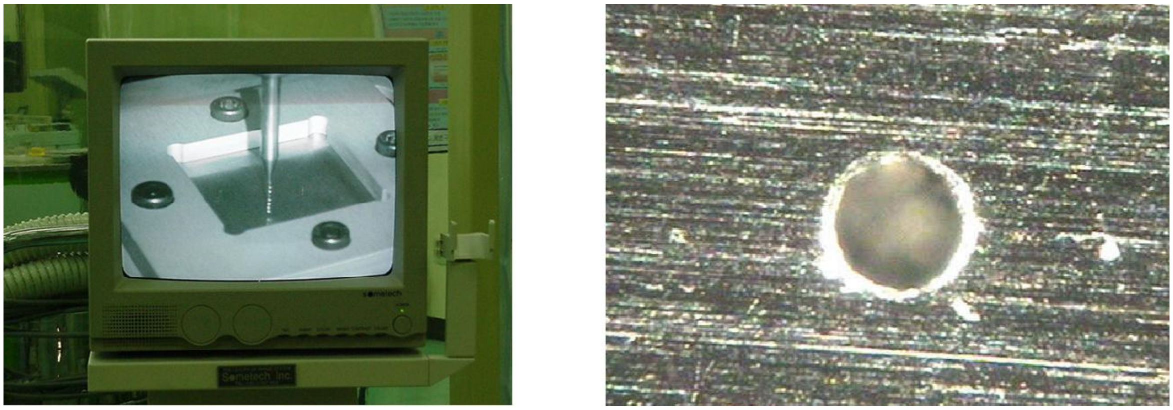

(a) Drilling process. (b) Machined 200μm hole (×300).

Fig. 6. Machined result of micro step drilling

Through the S/N ratio graphs and ANOVA, it can be observed that A1, B3, and C3 correspond to the factors producing minimal drilling thrust; there are no interactions between AxB and AxC. Thus, the optimal conditions are A1, B3, and C3. In the 200micro drilling process, the experimental works are carried out and ANOVA is also conducted. Through these works, it is possible to recognize that the sequence of the most influential factors for drilling thrust corresponds to feed rate, step-feed, and spindle rpm. In particular, it can be concluded that the feed rate is the most influential factor for drilling thrust. In this study, only the drilling thrust is taken into account as the most significant factor in order to optimize the step-feed micro drilling processes. It is possible, however, to consider other factors such as drill life, roughness, circularity of drilled holes, drilling time, burrs, etc. The selection of these factors depends on the main objectives of the required processes.

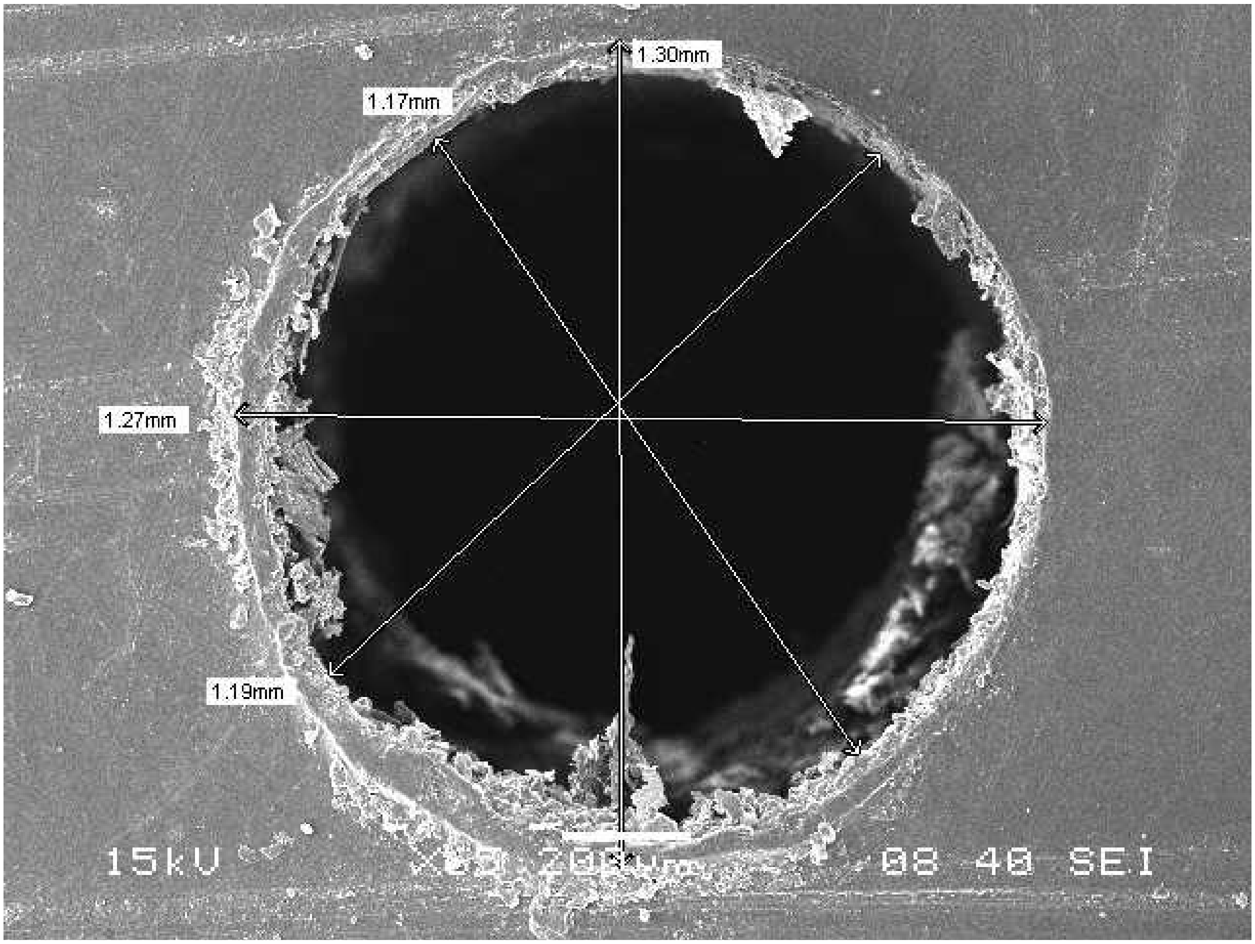

Fig. 7: Magnified view of micro drill holes under SEM
(Micro hole at Feed = 0.14 mm/rev, Speed = 90 rpm)

For cutting oil supplied drilling, the *burr* formed extent is diminished than dry drilling in a greater or less degree. The continuous flow type *chip* can be obtained distinctly relatively to dry drilling. The cutting force is lower degree of 5-15% than dry drilling distinctly. There is a little difference in cutting force between cutting oil supplied drilling and dry drilling as the hole diameter is smaller. A scanning electron microscope (SEM) is a type of electron microscope that produces images of a sample by scanning it with a focused beam of electrons. The electrons interact with atoms in the sample, producing various signals that can be detected and that contain information about the sample's surface topography and composition. The electron beam is generally scanned in a raster scan pattern, and the beam's position is combined with the detected signal to produce an image. SEM can achieve resolution better than 1 nanometer. Specimens can be observed in high vacuum, in low vacuum, (in environmental SEM) in wet conditions and at a wide range of cryogenic or elevated temperatures.

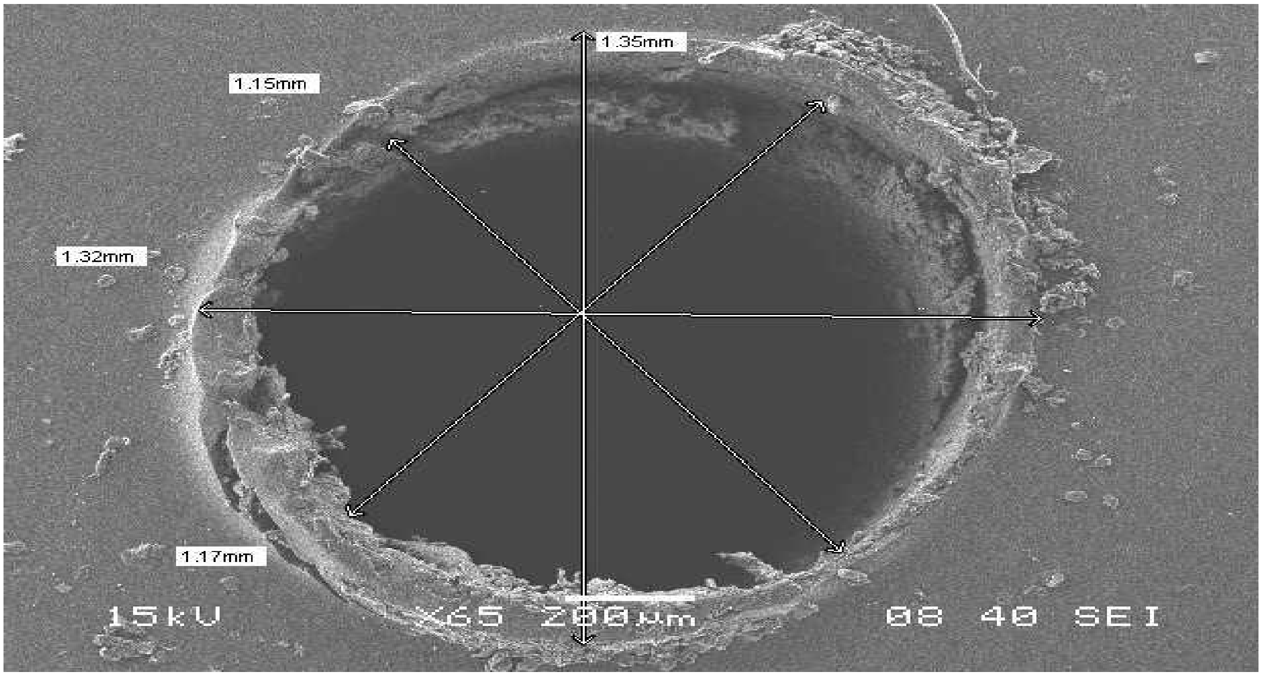

Fig. 8. Magnified view of micro drill holes under SEM
(Micro hole at Feed = 0.22 mm/rev, Speed = 140 rpm)

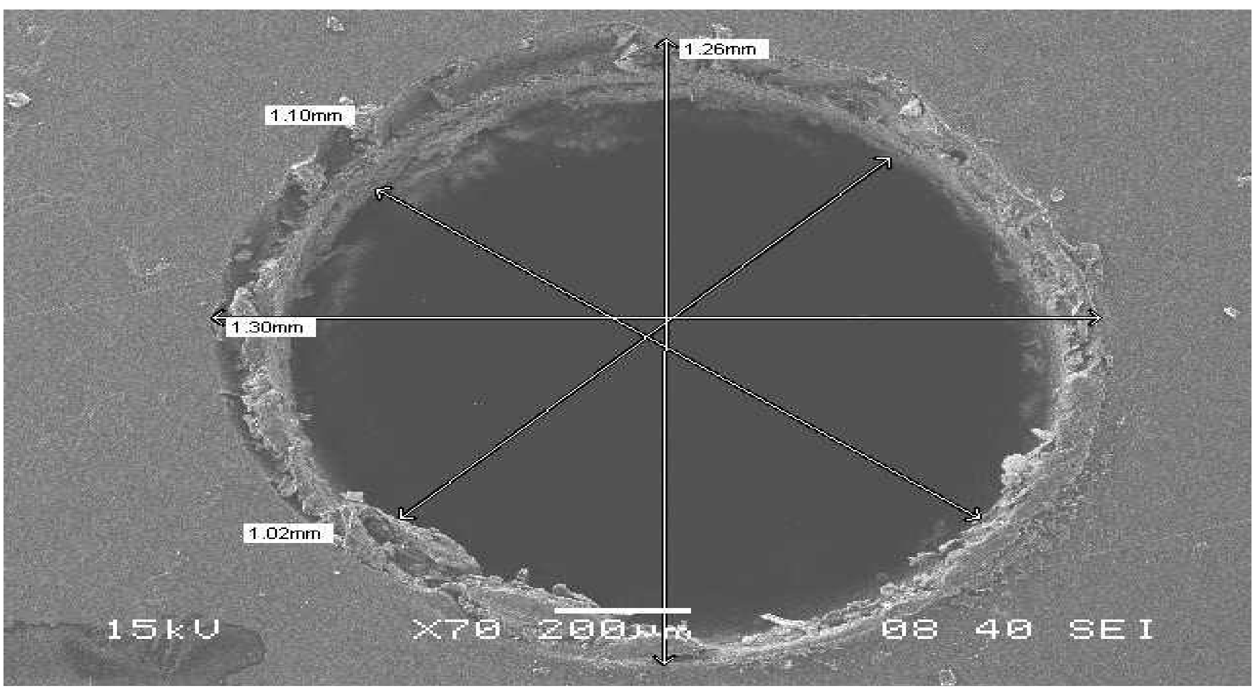

Fig. 9. Magnified view of micro drill holes under SEM
(Micro hole at Feed = 0.34 mm/rev, Speed = 320 rpm)

Conclusion

The objective of this study was to find out the optimized combination of Feed and Spindle speed so that the thrust force, circularity and burr formation can be minimized. The conclusions can be summarized as follows:

1. In the micro drilling process, the experimental work carried out by following the full factorial design, Optimal Parametric combinations were found out. Design of Experiment (DOE) is the efficient method in establishing relations with process and response parameters.

2. Through the S/N ratio graphs, it can be observed that S1 and N2 correspond to the factors producing minimal drilling thrust, Minimizing circularity error and reducing in burr size. Thus, the optimal conditions are feed of 0.14mm/rev and spindle speed of 140 rpm.

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