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MATHEMATICAL MODEL FOR THE PREDICTION OF ELECTRO-MAGNETIC WAVES ON QUALITY OF DRILLED HOLES IN COMPOSITE MATERIALS

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Abstract: Modern machining industries is mainly focusing its activities for the improvement of the product quality with less cost involvement in terms of work piece dimensional accuracy, surface finish, high production rate, less wear on the cutting tools, economy of machining in terms of cost saving and increase the performance of the product with reduced environmental impact. In this present work, the effect of electromagnetic field on achieving quality of drilled hole parameters in Glass Fibre Reinforced Polymer composite is investigated in terms of surface quality and the circularity of the drilled hole. The comparison has been made to investigate the machinability responses for drilling with and without electro-magnetic field. Electromagnetic field is applied on both sides of the drill bit using electromagnets during drilling process. The strength of the magnetic field is constant during the experiment by ensuring a constant current passing through the magnetic winding. Same drilling condition was used for both electro-magnetic drilling and normal drilling. The results show a better quality of the drilled surface and more accuracy in the circularity of the hole with the applied magnetic field compared to that obtained during drilling without using electromagnet in most of the cases. A mathematical model has also been developed by statistical approach using design expert to predict the quality of holes in terms of process parameters in electromagnetic drilling process.
Keywords: Glass Fiber Reinforced Polymer composite, CNC drilling Machine, Electromagnet, Surface quality, Circularity

1. INTRODUCTION

Composite Materials has attained a broad utilization area due to their several qualities such as lightness, rigidity, heat resistance, high endurance limit, good resistance to wear in space and aircraft industry, automobile industry, sports and marine materials. Although manufacturing industry has developed many unique methods of manufacturing with modern machining, the traditional hole drilling method is still the most commonly used operation process due to its economical and simple applicability. The quality of drilled hole on composite material is defined and assessed by several machinability factors. Among the two principal factors are the circularity of the hole and roughness of the inside surface. The objective of the current study is to investigate the effect of applying electro-magnetic field on the machinability responses. Many studies reported that the surface properties such as average surface roughness are critical to the function ability of machine components and to improve the surface quality of the machined surface many research works has been conducted [1]. Increased understanding of the surface generation mechanisms can be used to optimize machining process and to improve component functionability [2].

Numerous investigations have been conducted to determine the effect of different drilling parameters such as feed rate, spindle speed, drill diameter on surface quality. Mansori et al [3] studied the magnetic field effect on the tool wear and the feed force during drilling a mild steel work piece. A considerable decrease in tool wear and feed force has been observed during the experiment. K. S. Boparai et al. [4] studied the parametric optimization in drilling operation using surface response approach. In their study, the interaction of drilling input process parameters such as spindle speed, feed rate and number of holes and their influence on the surface roughness, diameter and position of hole obtained in drilling of mild steel. J. P. Nobre et al.[5] presented a methodology to quantify the effect of the drilling operation, during the application of the incremental hole-drilling technique (IHD) for measuring residual stresses in laminate composites, in particular, the polymer matrix composites (PMC). A. R. Ismail et al.,[6] in their study focused on the performance evaluation of two different commercial lubricants, which are EBL and EME salt to improve the lubricity of water based drilling fluid in drilling operation. The effect of magnetic field on surface roughness of the finished work piece during the turning process of mild steel has been studied by Anayet U Patwari et al. [7]. The authors observed a decrease in the surface roughness and significant improvement of tool life due to the application of magnetic field.

Serene [8] investigated the effect of magnetic field on the accuracy of the drilled hole with respect to change in the strength of the magnetic field and the polarity of the magnetic field. It has been shown that the magnetic field creates a damping effect on the drill bit which reduces the tool vibration and hence improves the tolerance. The exposed length of the drill bit was considered as another variable whose vibration affects the tolerance of the drill hole. Vibration and rapid wear lead to inaccuracy, poor surface finish and reduced tool life. It can be observed that most of the studies were based on steel. For the optimization of GFRP materials some research work has been conducted earlier based on harmony search algorithm [9]. The emphasis of this current study is to use glass fiber reinforced polymer (GFRP) composite material as the work material and the effect of electromagnetic field on drilled holes quality.

2. EXPERIMENTAL DETAILS

The drilling experiment was carried out on a CNC machine. The figure 1 below shows the schematic diagram of the experimental setup with Electromagnetic device and drilled surface.

The work piece used in this study is a glass fibre reinforced polymer composite with the following composition by weight as shown below, in Table 1.

Feed, Speed and drill diameter has been taken as process parameters. 3-level variation has been made to identify the process parameters effects on drilled surface quality and their interaction effects have also been investigated. The different process parameters variations are shown in table 2.

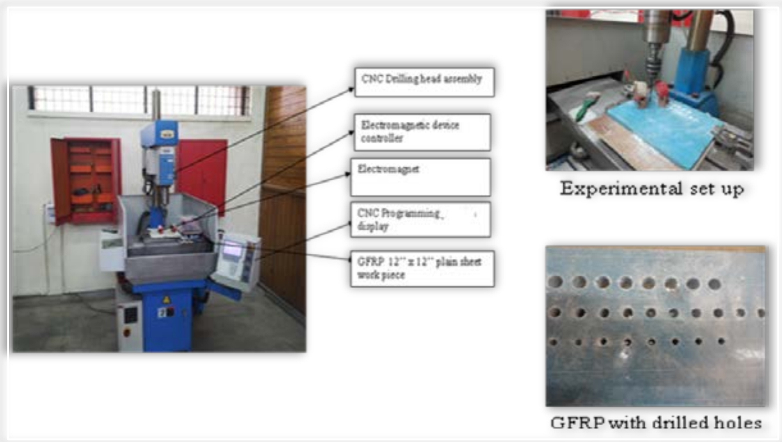

Figure 1. Experimental Set-up

Table 1. Material

Material	Glass fibre reinforced polymer composite		Resin 1.6 Glass fibre 0.73 MEKPO 0.032

Three different drill diameters used in the investigation to determine the effect of drill size on hole quality of GFRP composite during electro-magnetic and normal drilling processes. Flow sequence of experimentation and model development is shown in figure. 2.

Table 2. Process parameters used in this study.

Parameters	Values		
Feed (mm/min)	100	300	500
Speed (rpm)	500	750	1000
Drill diameter (mm)-Twist drill	6	9	12

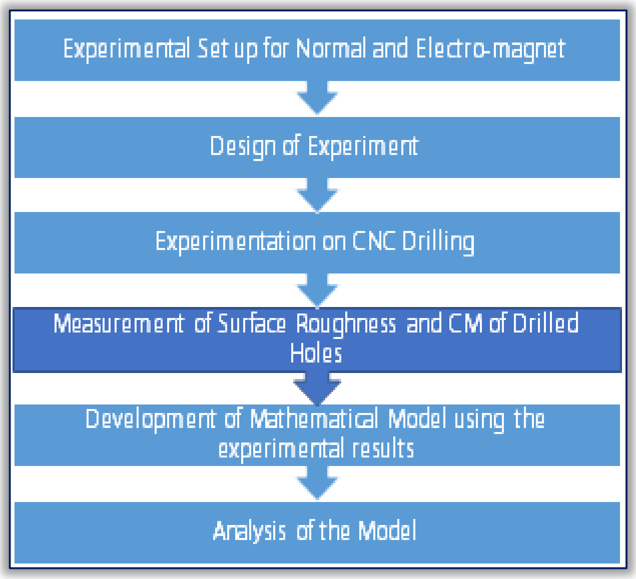

Figure 2. Flow Sequence of the experimentation and model development

17 holes with varying operating parameters were drilled and measurements were taken for surface roughness Ra and circularity. The variations of responses measured with respect to number of holes were compared between conditions with and without electro-magnetic field. A *Pictorial of* drilling on CNC machining centre without electro-magnet and the holes drilled using varying drilling parameters are shown in Figure 3.

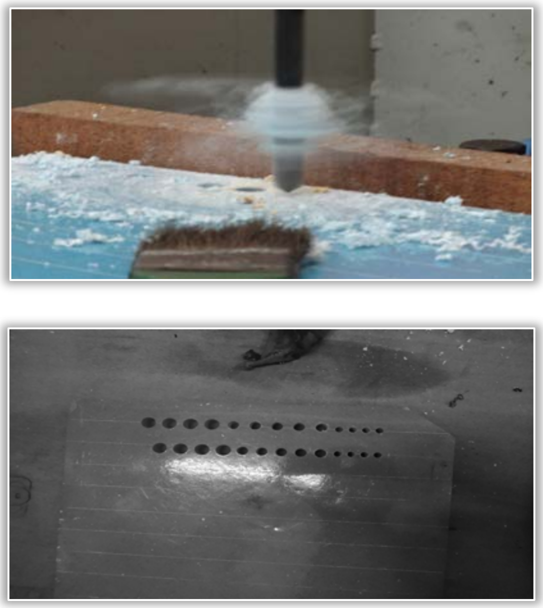

Figure 3. a) Experimental set up without electro-magnet; b) Drilled holes

3. ELECTRO-MAGNETIC SET UP

Fig 4 shows the electro-magnetic setup with a cable connection to the voltage regulator. The device is meant to control the current that passes through the coils which generate magnetic field. As electromagnet is a type of magnet in which the magnetic field is produced by the flow of electric current. An electric current flowing in a wire creates a magnetic field around the wire. To concentrate the magnetic field, in an electromagnet the wire is wound into a coil with many turns of wire lying side by side. The magnetic field of all the turns of wire passes through the center of the coil, creating a strong magnetic field there.

Much stronger magnetic fields are produced as "core" of ferromagnetic material, such as soft iron, is placed inside the coil. The ferromagnetic core increases the magnetic field to thousands of times the strength of the field of the coil alone, due to the high magnetic permeability (μ) of the ferromagnetic material. In this study, an electromagnet was manufactured by using mild steel core and copper wire. Instead of using a solid mild steel core, several layers of mild steel sheets were used to make the core as shown in fig. 4 with the circuit diagram. This arrangement ensures minimum eddy current loss. Copper wire with 200 turns made up each coil.

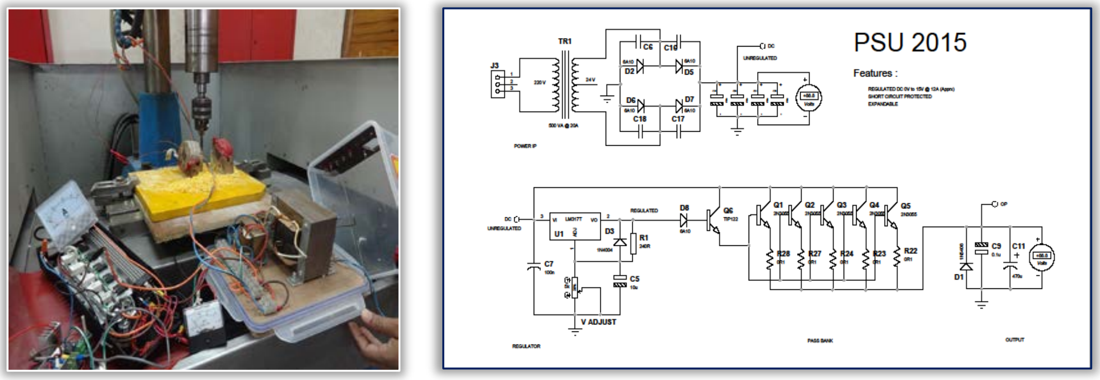

Figure 4: Electro-magnetic setup used in this study

4. MEASUREMENT OF SURFACE ROUGHNESS AND CIRCULARITY

Figure 5 show a stylus surface roughness measurement instrument called Mitutoyo Surftest SJ-210 (178-561-02A). A portable, handheld surface roughness tester with a 2.4-inch, colour, backlit, LCD touch screen that displays in vertical or horizontal orientations, and left- and right-hand data views in 16 languages. Measures 39 parameters, and has a micro-SD card that stores up to 10,000 results.

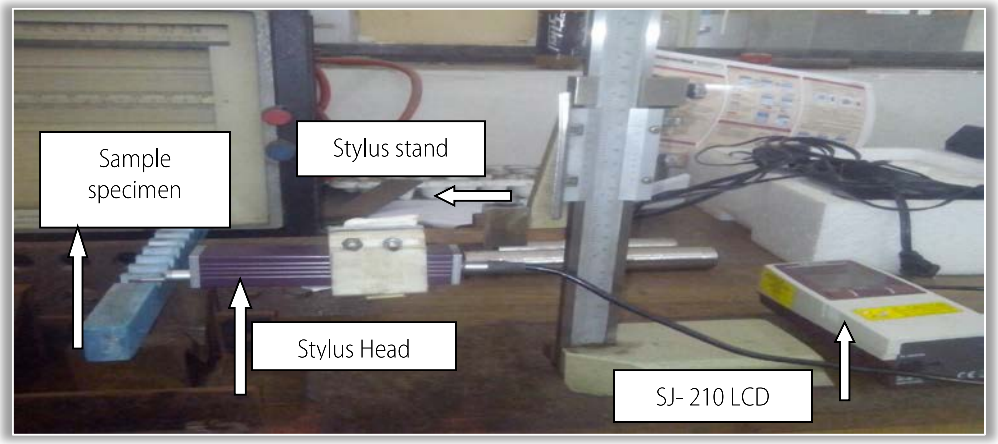

Figure 5. Surface Roughness Tester: Mitutoyo Surftest S.J. 210

This surface tester has an Ingress-Protection (IP)-53 rating for water and dust resistance. It displays total and sectional measurement results, assessed profiles, evaluation curve, bearing area curve (BAC), and amplitude distribution curve (ADC), and waveform results. The SJ-210 has auto-calibration that can be initiated with numerical value entry, and gain adjustment for colour clarity. Drilling operations with 6 mm, 9 mm and 12 mm drill diameter were performed on the GFRP composite under two different working conditions and average surface roughness were measured for all the drilled holes according to the designed experimental flow sheet.

5. CIRCULARITY MATRIC

Circularity is one of the most important parameter to check drilled holes quality performance. It is defined as a two dimensional geometric tolerance that controls how much a feature can deviate from a perfect circle. Circularity indicates diametric tolerance between size of drill and size of hole which are two mating parts.

Measurement of circularity is done by Co-ordinate measuring machine (CMM). For drilling operation, it can also be measured by taking difference between diameter of drill and the holes diameter measured. However, in this study, the circularity was calculated by the following formula.

$$CM= 4*\Pi*(Area)^2/ (perimeter)^2$$

The procedure involved for measuring the diameter of the drilled holes using internal calliper with the measurement of the perimeter of the hole using thread and scale rule and finally from the values obtained, the circularity was calculated using the formula

6. RESULT AND DISCUSSION

— Surface roughness

Experimental design has been made based on three level variations for fitting responses using Box Behnken design. 17 experiments have been conducted for both electromagnetic set up and without electro-magnetic conditions. For all the drilled holes surface roughness has been measured accordingly. All the measured results for both the conditions are shown in table 3.

The surface quality of the drill hole shows improvement in some cutting conditions when magnetic field is applied compared to the case when no magnet is used during drilling process as shown in table 3. It can be seen from the results that at high speed and low feed, the surface roughness measured with electromagnet is low.

Meanwhile, at high feed and high speed, the effect of electromagnetic force was not felt in which the surface roughness has high response. As a result of high feed, a high thrust force is generated while drilling GFRP material and the characteristic damping effect the application of electromagnetic force has on the drill diameter is only effective on small drill size.

Table 3: Results of Ra

Run	Feed mm/min	Speed Rpm	Drill Diameter Mm	Response Surface Roughness Micro-m	
				normal	With Electro-magnet
1	300	1000	6	10.255	9.128
2	300	1000	12	6.536	10.367
3	300	500	12	5.803	13.470
4	300	750	9	3.814	7.722
5	500	1000	9	6.152	6.084
6	100	1000	9	6.987	4.072
7	300	750	9	4.1	7
8	300	750	9	5.2	7.8
9	500	750	6	10.558	8.616
10	300	500	6	10.719	8.299
11	300	750	9	3.7	7.4
12	100	750	6	9.528	5.698
13	100	500	9	8.59	3.736
14	500	750	12	6.690	11.222
15	100	750	12	4.993	8.737
16	300	750	9	3.8	8
17	500	500	9	5.883	8.775

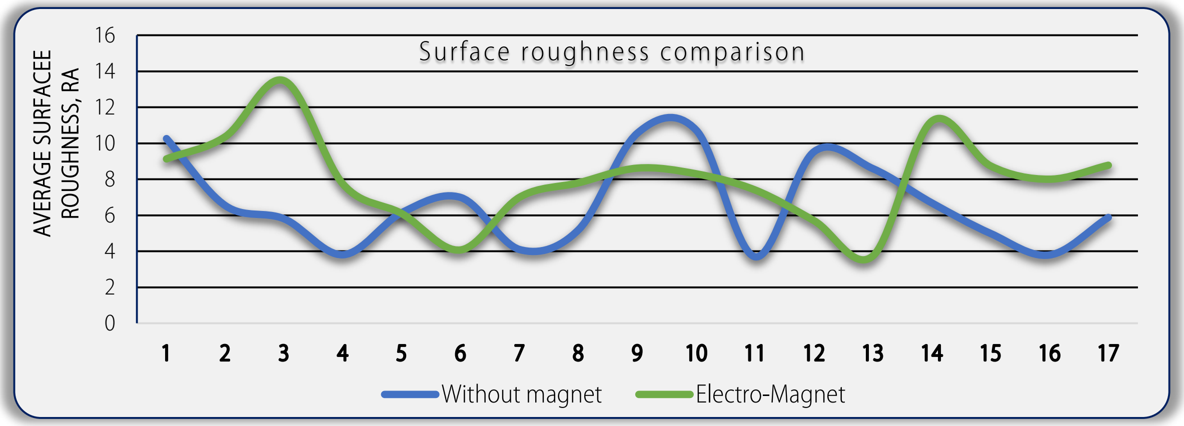

Figure: 6: Statistical Analysis of the Models

The graph in fig. 6 compares the responses of drilling operations under the two different environments. It can be seen from the graph that the responses from the experiment with magnet has a better output then followed by the normal condition. The responses obtained through the application of electromagnet produces decrease in surface roughness at 6mm diameter as compared to the other two environments. This indicates the effect of magnetic force on 6 mm diameter which creates a damping effect on the drill bit which reduces the tool vibration and hence improves the tolerance. However, because of the low effect of magnetic force on 9 mm and 12 mm drill diameter, the roughness values differ.

— Mathematical Model development

A mathematical model has been developed to predict the drilled hole surface quality using electromagnetic field. From the experimental results, as in table 2, a quadratic model has been developed considering the results of Sum of Squares, Fit and Summary test, and model Statistics. The confidence level of the model was obtained using ANOVA.

Conditions	Mathematical Equation
Electro-Magnet	$Ln(Ra) = +1.85752+7.60981E\text{-}003 * A+3.36504E\text{-}003 * B -0.57254 * C-6.83656E\text{-}006 * A^2 - 1.22582E\text{-}006 * B^2 +0.040917 * C^2 -2.26182E\text{-}006 * A * B -6.79985E\text{-}005 * A * C -1.19016E\text{-}004 * B * C$

— Statistical Analysis of the Models

The suitability and accuracy of the developed quadratic models was examined using various statistical tools and graphical plots, such as: (1) Normal Plot of Residuals, (2) Perturbation, (3) Effects of Process parameters.

It can be observed from the plots that the residuals generally fall on a straight line implying that the errors are distributed normally. The trend for different drilling conditions is similar justifying the suitability and accuracy of the quadratic model developed. The perturbation graphs show the interplay between the three drilling parameters considered for this experiment. It can be seen from the perturbation graphs that the significant factors are A and C which are also confirmed from the results of the experiments. Since the perturbation curve shows the effect of each process input parameter on speed with a reference point at A:300. B:750 and C:9. Then, at this point, the three input parameters meet to achieve minimum dimensional deviation.

The 3D surface graph shows in figure 7 the interaction effect of spindle speed and feed rate on surface roughness. As the spindle speed and the feed rate varies and the drill diameter is kept constant at 9.0nmm as shown above, the surface roughness decreases for all the three feed rates and conditions as the spindle speed is increased from 500 to 1000 rpm. This decreasing trend is not changed in two out of the three levels of feed rate. Hence the interaction effect of spindle speed and feed rate is less significant.

From the response surface plot, it is noted that the surface roughness reaches a maximum of 8.59 µm when the spindle speed is at 500 rpm and the feed rate is at 100 mm/min. It reaches a minimum of 3.814 µm when the spindle speed is at 750 rpm and the feed rate is at 300 mm/min. High level spindle speed combined with low level feed rate gives optimum surface roughness.

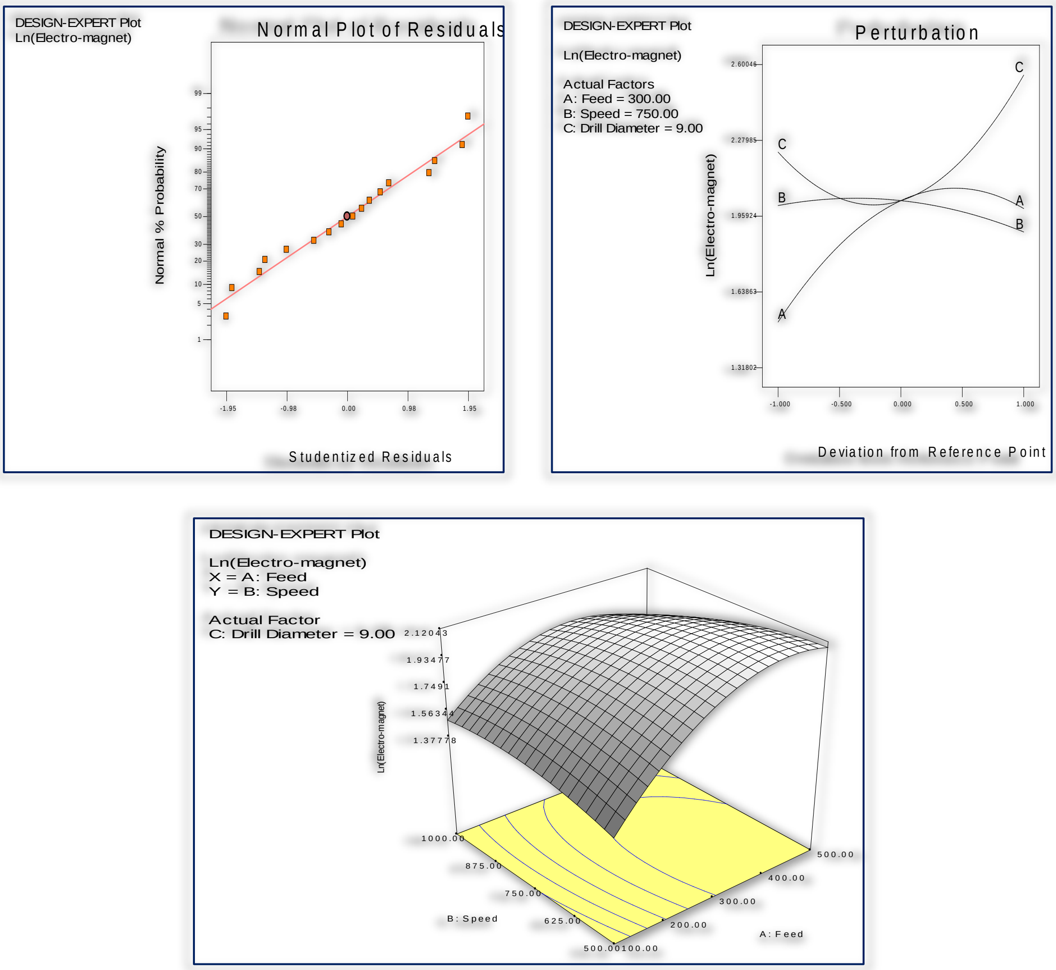

Figure: 7: Statistical Analysis of the Models

— Circularity Matric

From the computed results, it can be seen that there was no much variation on the circularity on the holes drilled under the different conditions. All the computed values are either 1 or very close to 1.

The index 1 means the hole is completely circular. Lower the value of the circularity index indicates less circularity of the drilled holes shape. From the circularity results it is clear that magnetic field causes the drill bit to produce an almost uniform circular hole compared to non-magnetic drilling. The circularity of the drilled hole with electro-magnet and without electro-magnet was shown in figure 8.

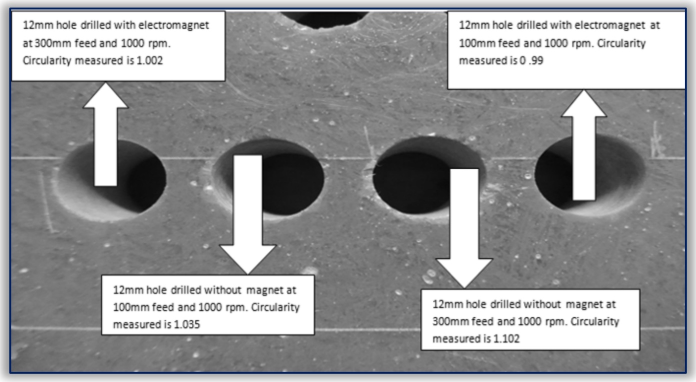

Figure 8: Specimen picture

7. CONCLUSION

The surface quality of GFRP composite material which is characterized with roughness and circularity was investigated experimentally using different drill diameter, speed, feed and drilling condition of with and without electro-magnetic force. It was observed that the presence of electro-magnetic force during drilling operation improved the quality of drilled hole by decreasing the vibration of the drill bit which results in the in-line movement of the drill bit thereby improving the surface roughness and the circularity of the drilled hole.

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