International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-5 Issue-1, October 2015

Experimental Investigation of Surface Integrity of End milled CFRP Composites

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Abstract – In general, the quality of the surface produced during machining is affected by the process variables and the vibrations of the tool. The surface finish is affected by the undesired vibrations that occur especially when a rotating tool like drill/ milling cutter is involved. Machining of fiber reinforced composites plays a vital role in obtaining fine tolerances on their components so as to assemble and integrate them with the other components. Carbon Fiber Reinforced Polymer (CFRP) composites are rapidly substituting the conventional materials as they meet high performance requirements due to their high specific stiffness, strength and corrosion resistance. In this study, the effect of process parameters on the dimensional accuracy and surface finish of the slots produced by end milling on CFRP laminate is studied. Experimental investigation is carried out to determine the relationship between spindle speed and feed which minimizes the surface roughness and delamination factor. The variation of the cutting forces involved is also studied in relation with the process variables to derive the regression equations.

Index terms: CFRP, Delamination factor, End Milling, Surface Integrity

I. INTRODUCTION

Advanced composite materials have been continuously engineered to meet high performance requirements in various fields. These materials can be tailored such that their properties match the specific industrial and consumer product requirements. With the ever improving processing and fabrication techniques, advanced composites offer a cutting edge over the conventional materials in high performance applications. Among the various types of composite materials, fiber-reinforced polymer (FRP) composites have been attractive and extensively used. Infact, conventional metallic materials have been largely replaced by FRP composites in many cases. The applications of FRP composites' range from highly critical aerospace components (e.g. tails, wings, fuselages), to racing car bodies and chassis, sporting goods (e.g. bicycle frames, surf/snow boards), and marine parts (e.g. hulls, decks). Ease of processing and lesser raw materials cost essentially makes them suitable for the above mentioned structural and functional requirements.

Manuscript published on 30 October 2015.
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FRP composites have high specific stiffness and specific strength along with better corrosion resistance over the metal alloys and their metal matrix composites (MMCs) counterparts. Their appealing properties can also be deliberately tailored to improve fire resistance, Thermal and electric insulation as well as sound absorption. These make them desirable for non-structural products, in areas, such as the panel or acoustic wall applications. Despite their excellent physical and mechanical performance, FRP composites are known for their inherently poor machinability compared to that of monolithic materials due to heterogeneity of materials. A.I.Azmi et al. [1] have discussed the machinability of glass fiber reinforced composites (GFRP) during end milling by using Taguchi's method of design of experiment. Their work aimed to elucidate the machinability of GFRP composites with respect to surface roughness, tool life and machining forces. Experiments were conducted by considering different parameters (cutting speed, feed rate and depth of cut) and three levels according to the Taguchi design of experiment method. Taguchi analysis combined with statistical analysis of variance (ANOVA) was performed to quantify the effects of the above variables on those characteristics. Validation tests under randomly selected machining conditions have further demonstrated the feasibility of the developed mathematical models with 8-12% error for tool life and machining forces predictions while >19% error for calculating the surface roughness. Karpat et al. [6] proposed a mechanistic force model for milling of CFRP by collecting cutting force data during slot milling of CFRP using polycrystalline diamond cutters. The model is shown to be capable of predicting cutting force during milling of multidirectional CFRP laminates. The relationship is represented with simple sine functions. Hocheng and Puw [3] investigated the cutting of uni-directional CFRP composites using a single square carbide insert. The experiments were conducted at cutting speeds ranging from 30 – 190 m/min, table feed speed of 50 to 150 mm/min and a constant depth of 1 mm. Based on the results, the authors asserted that work piece fiber orientation has a significant effect on the formation of burrs and surface roughness. The cut was clean showing no fiber roots on the machined surface when the tool was fed along the fiber orientation (0° fiber orientation). Many uncut fibers were, unfavorably, observed when machining at 90° and 45° fiber angle, as the cutting tool is liable to slip over the fibers during cutting. J.Paulo Davim et al.[5] evaluated the cutting parameter in case of milling of GFRP composites with the aim to minimize the delamination factor and maximize the surface finish. ANOVA technique was utilized to conclude the set of optimum cutting parameters.

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Rahman et al.[10] studied the machinability of CFRP composites with various cutting parameters with three types of cutting tool materials, namely uncoated carbides, ceramic and Cubic Boron nitride (CBN). The CFRP specimens had short (discontinuous) and long (continuous) fiber reinforcements. It was reported that the carbide tool performed better at low cutting speeds, whereas the performance of CBN tool surpassed the others at high cutting speeds. Koplev et al.[8] contributed the first chip formation studies through orthogonal cutting of CFRP composites in the 0^o and 90^o fiber orientations. The authors claimed that the substantial difference between machining of FRP composites and metal was that the chips were not subjected to a large plastic deformation during cutting. The limitation of Koplev's work is in the fact that only two fiber orientations (0^o and 90^o) were taken into consideration. In view of this, Takeyama and Ijima [13] included other work piece fiber angles ranging from 0^o, 30^o, 45^o, 60^o to 90^o in their chip formation studies of GFRP composites. Calzada et al.[9] proposed a model for failure mechanism of fiber as a function its orientation while micro-milling of CFRP composites. The carbon fibers oriented at 90^o and 45^o degrees to the direction of motion of the cutting tool were exhibited to fail predominantly by crushing/compression. On the other hand, the buckling and bending-dominated tensile failures were observed for the 0^o and 135^o orientations respectively. Devi Kalla et al. [6] developed a methodology for predicting the cutting forces by transforming specific cutting energies from orthogonal cutting to oblique cutting of CFRP composites. R.Madoliat, S.Hayati et al., [12] investigated the suppression of chatter slender end mill via a frictional damper. It was shown that the friction damper improved the quality of surface finish produced during the end milling process. N. Feito et al. [9] developed finite element model for the complete drilling process in order to predict the delamination factor in case of drilling of CFRP composites. The authors also presented a simplified model which reduced the computational cost with a slight over rated estimate of delamination factor. Carlos Santiuste et. al[3], studied the orthogonal cutting of long fiber composites. A Finite Element model was developed to analyze the chip formation mechanisms in case of Glass and Carbon Fiber Reinforced Polymer (FRP) composites. There were significant differences found when comparing the machining induced damage predicted by the model for these composites. It was observed that the damage occurred ahead of the interface and beneath the tool tip in case of GFRP composites. The damage was localized in a smaller zone in case of CFRP.

II. FABRICATION AND TESTING

The Carbon fiber reinforced polymer laminate comprises of bi-directional woven Carbon fiber fabric with fiber orientation ($0^0/90^0$) and epoxy(LY556) as the matrix along with hardener, LY551.The carbon fiber cloth is cut to the required size (330mmx170mm) and the laminate is produced by compression molding process. It consists of 20 layers to make up a thickness of 8±0.1mm. The laminate so produced is first tested for its mechanical properties like Ultimate tensile strength, Flexural strength and hardness. The mechanical properties of the CFRP laminate are tested which are given in the table 1.

Table i: Properties of CFRP

S. No	Property	Average Value
1	Shore hardness (D scale)	93.3
2	Ultimate Tensile strength	620 MPa
3	Ultimate shear strength	31MPa

III. EXPERIMENTATION

The experimentation is carried out on a conventional vertical spindle Universal milling machine. The machine table carries a milling dynamometer with its probes attached to the display. The general principle of end milling process is shown in figure 1. The width of the work piece is limited by the width of the vice of the dynamometer. Two different end mills made up of High Speed Steel and Cemented carbide are used as shown in figure 2. The specifications of these tools are provided in table 2.The experiments are planned as per the L9 Orthogonal array as this study involves two factors (spindle speed, feed rate) at three levels. The end milling is carried out at three different spindle speeds of 315, 500 and 800 rpm while three different feed rates considered are 32, 40 and 63mm/min. The selection of these levels is based on the available speeds and feeds on the universal milling machine. The depth of cut is maintained as 0.2mm throughout the experimentation.

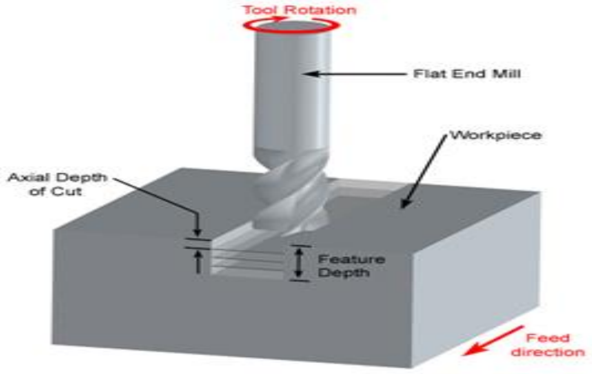

Fig.1: General principle of End milling process

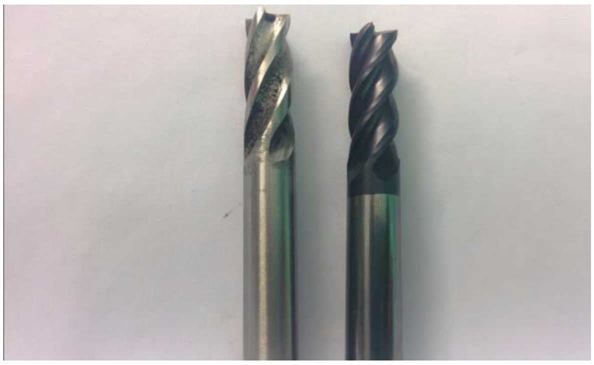

Fig.2: HSS and Cemented Carbide End mills

Table ii: Tool Specifications

Grade	K20 (94% WC), HSS
Diameter	6 mm
Number of flutes	4
Helix, Relief & Clearance angle	30^0, 9^0, 16^0

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Milling is carried out under dry conditions to produce slots of 6mm width as shown in figure 3. A vacuum pump is used to clean the dust and chips produced during this process. All the three components of machining forces i.e. thrust force (F_Z), feed force (F_Y) and cutting force (F_X) are measured by the dynamometer. The thrust force is observed to remain relatively constant while the feed force and cutting forces vary with respect to the process parameters. The total machining force F is the resultant of its components given by

$$F = \sqrt{F_X^2 + F_Y^2 + F_Z^2}$$

The slipping/sliding of HSS tool on the work piece surface without any cutting was observed at lower speeds while the carbide tool performed well. This was due to the fusion and adhering of resin on the cutting edges as shown in figure 5. This phenomenon may be attributed to the large cutting forces encountered by the tool at lower speeds and the thermal properties of tool work piece combination. It was concluded that carbide tool was a better choice for milling CFRP rather than HSS and hence all the experiments were performed with the carbide tool.

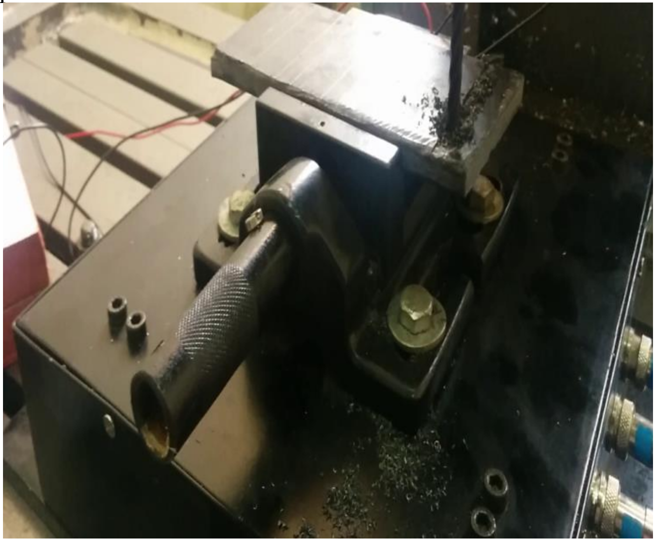

Fig.3: End milling of CFRP laminate

An AVD vibration tester is used to measure the amplitude, velocity and acceleration of vibration produced during machining. The machined surface is further analysed for its geometrical accuracy in terms of delamination factor. Delamination factor is defined as the ratio of the maximum width of the end milled slot to the theoritical width of the slot as shown in figure 4. The actual width is measured using OptoMech Profile Projector which has a resolution of one micron and magnification of 30X.

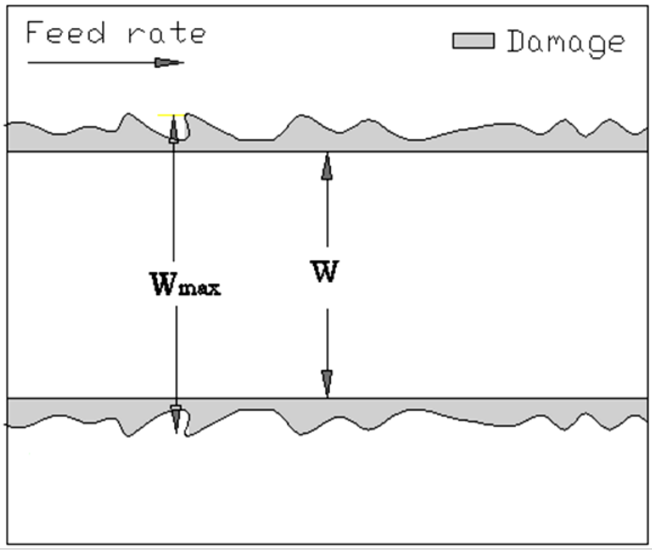

Fig.4: Measurement of slot width with maximum damage (W_{max}) and nominal width (W)

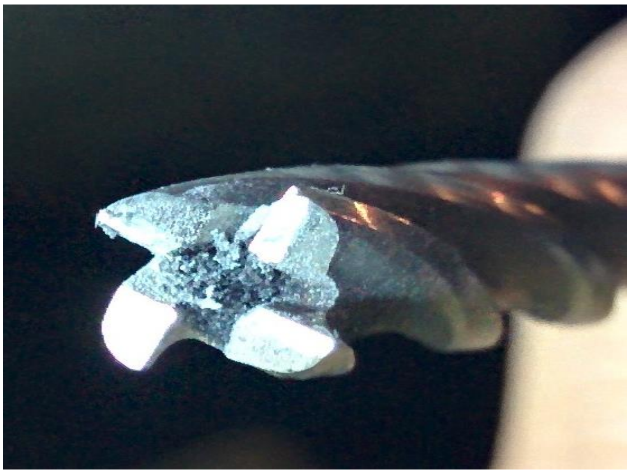

Fig.5: Adhering of epoxy resin on tip of HSS End mill

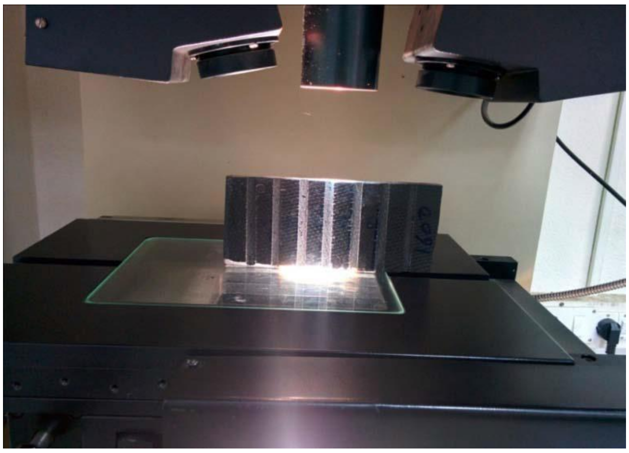

Fig.6: Measurement of slot width using Profile Projector

IV. RESULTS AND DISCUSSION

It can be observed from figure 7 that the machining force (*F*) increases with an increase in the feed rate but decreases with an increase in the spindle speed.

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The delamination factor (F_d) also increases with an increase in both the spindle speed and feed rate as observed in figure 8. It is also observed that as feed is increased, the quality of the surface finish deteriorates on the CFRP composite as shown in figure 9. The same feed at higher speeds resulted in an improvement of the surface finish which is generally the characteristic feature observed in case of machining of isotropic materials. It is seen that higher feeds are resulting in an increase in the machining force which are in turn increasing the delamination factor.

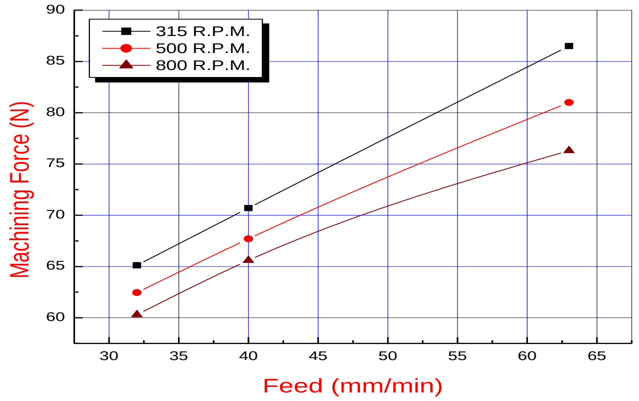

Fig.7: Variation of Machining force w.r.t Feed

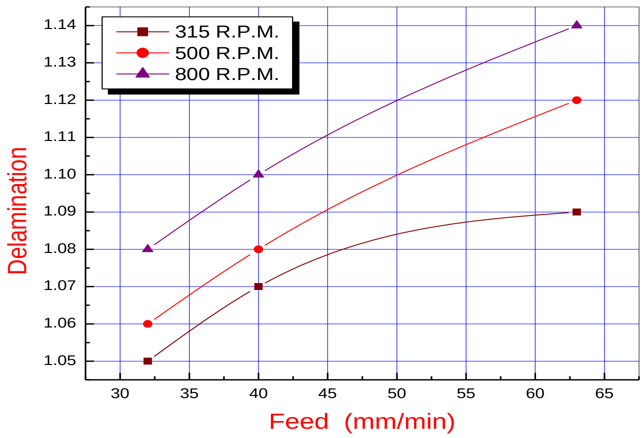

Fig. 8: Variation of Delamination w.r.t Feed

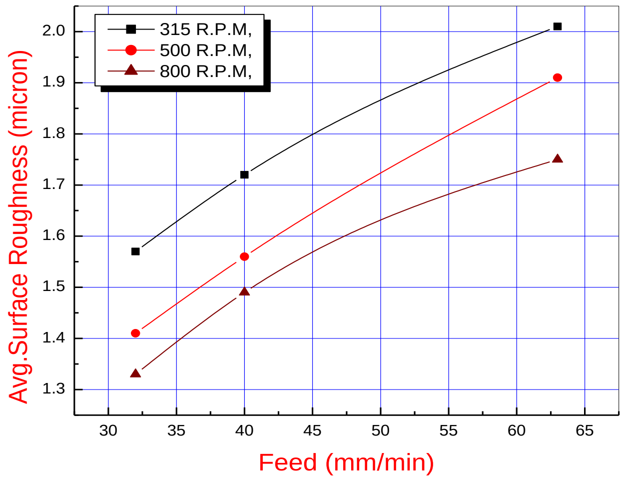

Fig. 9: Variation of Surface Roughness w.r.t Feed

V. REGRESSION ANALYSIS

Regression analysis is carried out in order to arrive at a relationship between the average surface roughness, spindle speed and feed. Similarly, regression equation is developed for the delamination factor in terms of spindle speed and feed. The surface plot of surface roughness and delamination factor with respect to the variation of speed and feed are shown in figures 10 and figure 12. The normal probability plot of the residuals shown in figures 11 and figure 13 indicate that deviations of these residuals from the fitted line are very less.

i) Average Surface Roughness versus feed, speed The regression equation for the average surface roughness is

Avg. Surface Roughness = 1.32 + 0.0136 feed - 0.000491 speed.

Predictor	**Coef**	**SE Coef**	**T**	**P**
Constant	1.31717	0.09890	13.32	0.000
feed	0.013565	0.001684	8.06	0.000
speed	0.0004909	0.0001107	-4.43	0.004

S = 0.0663734 R-Sq = 93.4% R-Sq(adj) = 91.2%

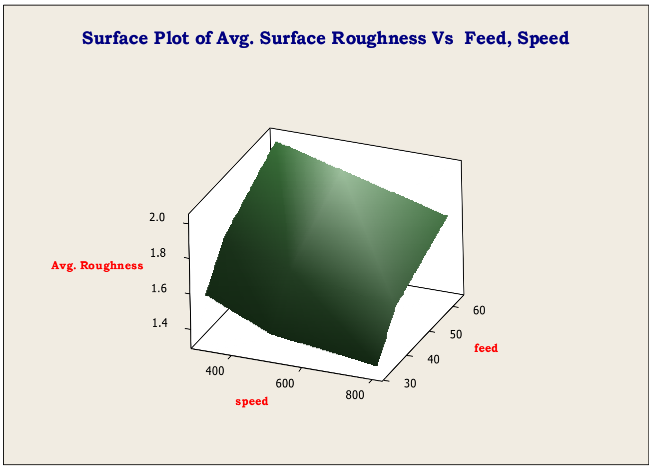

Fig. 10: Surface plot of Avg. Surface Roughness Vs feed, speed

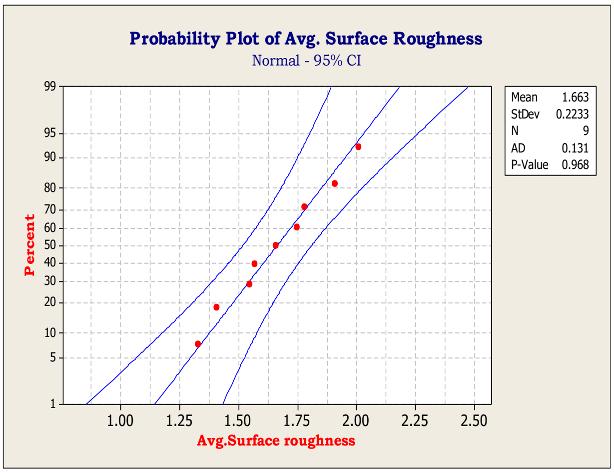

Fig. 11: Probability plot of residuals of Avg. Surface Roughness

ii) Delamination factor versus feed, speed The regression equation for delamination is Delamination Factor = 0.973 + 0.00166 feed + 0.000075 speed

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Predictor	Coef	SE Coef	T	P
Constant	0.972830	0.009885	98.41	0.000
feed	0.0016602	0.0001683	9.87	0.000
speed	0.0000747	0.00001106	6.76	0.001

S = 0.00663376 R-Sq = 96.0% R-Sq(adj)=94.6%

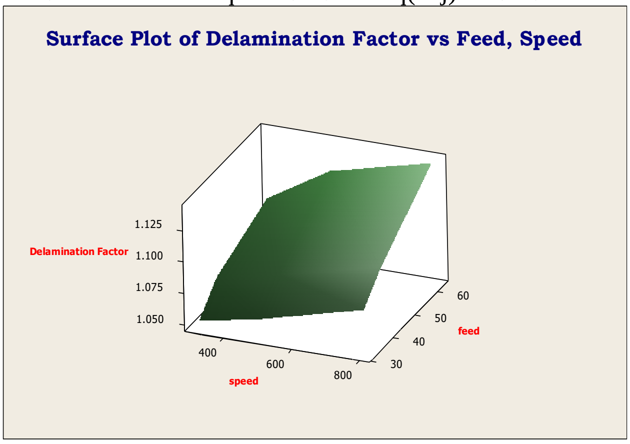

Fig. 12: Surface plot of Delamination Factor Vs feed, speed

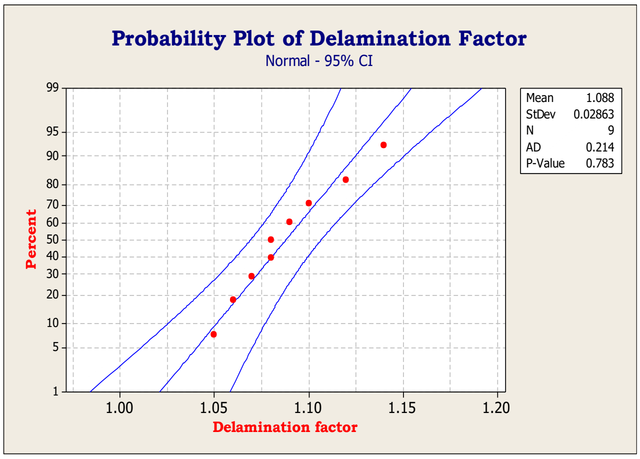

Fig. 13: Probability plot of residuals of Avg. Surface Roughness

VI. CONCLUSIONS

The effect of various process variables on the key machinability parameters of CFRP have been investigated through Taguchi design of experiments. It can be concluded from the above investigation that the feed rate has the highest influence on the surface roughness and the delamination factor of the CFRP materials when the depth of cut is maintained constant. Though increasing the spindle speed is improving the surface finish but it may result in tool wear and thus reduce the tool life.

ACKNOWLEDGEMENT

The authors would like to thank the help extended by M/s Anand Composites in the procurement of the raw materials and the subsequent fabrication process of CFRP laminates.

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