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Experimental investigation on comparison of the surface quality on various GFRP composites during end milling by control process parameters

I.S.N.V.R.Prasanth[1], Dr.D.V. Ravishankar[2], Dr.M.Manzoor Hussain[3]
[1](Associate Professor, Department of Mechanical Engineering, St Mary's integrated campus, Hyderabad,India)
[2](Professor and Principal T.K.R.CET, Hyderabad, Telangana, India)
[3](Professor and Principal, J.N.T.U, Sultanpur, India)

Abstract: *In this research work, the effect of process parameters on the dimensional accuracy, surface finish and damages of the slots produced by end milling on GFRP composite laminate is studied. Machining is necessary to obtain close dimensional accuracy with minimized surface damages towards the selection of best milling processes parameters such as spindle speed, feed rate and depth of cut. This paper presents the investigation results pertaining to resultant force, surface roughness and delamination aspects of uni-directional (UD) (+45/-45*^{0}*) and bi-directional (BD) (0*^{0}*/90*^{0}*) glass fibre reinforced composite laminates by machining with 10mm solid carbide end mill cutter. To differentiate the machinability quality of uni-directional (UD) (+45/-45*^{0}*) and bi-directional (BD) (0*^{0}*/90*$^{0)}$ *glass fibre reinforced plastics is an important aspect in production industries such as automobile, aerospace and other industrial applications. Therefore the experiments were designed as per Taguchi DOE techniques and thoroughly investigated to drawn useful conclusions, software MINITAB17 is used in the process.*

Keywords: *End milling, Machinability, Taguchi's DOE, Uni- directional (UD) and bi-directional (BD) GFRP composite laminates.*

I. Introduction

Fiber reinforced polymer composites (FRP) are alternative materials to produce wide range of applications of conventional materials (metals) in automobile and aerospace industries. They are extensively used in commercial applications due to their mechanical properties such as high strength to weight ratio, high stiffness, ease of manufacturing and good corrosion resistance. In order to understand the milling of glass fiber reinforces plastic composite materials appreciably effected by delamination damage and surface roughness damage under the action of machining process parameters. For this reason to improve the surface integrity quality and minimize the delamination, interlayer fracture, splintering and fiber/ resin pull out, to conduct the number of experiments by design of experiments to reach optimal solutions such as reduce the damages and will get the good surface finish Smith WF [1] , Davim etal. [2] studied the influence of cutting process parameters on surface roughness in turning of GFRP composites using statistical analysis, and he suggested that the feed rate is mainly effected parameter on the surface integrity. Santhanakrishman et al. [3] and Ramulu et al. [4] carried out a study on machining of polymeric composites and concluded that an increasing of the cutting speed obtained a better surface finish. The users of FRP are facing so many difficulties when machining it, because technical back ground acquired for conventional materials cannot be applied for such new materials, whose ability to machining is different from that of conventional materials , thus it is desirable to experimentally investigate the behavior of FRPs during the machining process. And also studied how the fiber orientation significance on the quality of machined surfaces and tool wear rate. Machining of composite materials depends on the type of fiber inserted in the composites, particularly by the mechanical properties. On the other hand, the selection of parameters and tool are dependent on the type of fiber inserted in the composites and which is very important in the machining process. Kaneeda. [5] studied the principal cutting mechanisms correlate strongly to fiber arrangement and tool signature; he concluded that surface finishing the ANOVA analysis has pointed out that the surface roughness decrease by increasing the feed and speed. Pau and Hocheng. [6] studied how the fiber orientation effect on the surface integrity and tool wear rate, moreover selection of process parameters and tools are depending on the types of fibers arrangement in composites and which is very useful in machining process. Reddy srinivasulu. [7] investigated on influence of cutting process parameters on surface roughness and delamination factor on GFRP during end milling, Taguchi method is used to investigate the machining characteristics of GFRP and results of ANOVA finally concluded by using artificial neural network. The result of ANOVA for surface roughness, depth of cut has the more significant parameter for affecting the surface roughness and delamination damage. Palanikumar et al. [8] got experimentally measurement of surface finish in FRP is less affected compare to that in metals, because of FRP arrangement may cause to errors it will also cause the fiber stacks on the stylus, and he developed a procedure to evaluate and optimize the selected factors to achieve minimum surface damage by integrating Taguchi method and analysis of variance (ANOVA) technique. J. Paulo Davim et al. [9] provided a better understanding of the machinability of PA 66 polyamide with and without 30% glass fiber reinforcing, when precision turning at different feed rates and using four distinct tool materials. The findings indicated that the radial force component presented highest values, followed by the cutting and feed forces. The PCD tool provided the lowest force values associated with best surface finish, followed by the ISO grade K15 uncoated carbide tool with chip breaker when machining reinforced polyamide. J. Paulo Davim and Enemouh EU [10-11] as the tool progresses into the work piece, the fibers are subjected to compressive loading along the axial direction. In recent literature surveys, it is observed that experimental studies are importantly supported with different modeling's, analysis and optimization techniques to minimize the number of complications, time consumption and expensive experiments. Bhatnagar.et al. [12] the fiber orientation, poor surface roughness like fiber breaking , matrix damages , inter laminar delamination failures generally seen if machining is done by improper machining conditions. The mechanistic modeling approach for predicting cutting forces in the milling process of carbon fiber reinforced composites. In this regard present investigation have filled the gap of previous researchers work on machined different GFRP composite laminates by Taguchi design method, the model was based on experimental obtained data was developed to predicted the surface roughness and delamination factor in solid carbide end mill cutter of two different types of GFRP composite laminate plates. Here the three input factors are machining parameters (Speeds are 1153rpm, 1950 rpm, 2500 rpm, feeds are 1 mm/sec, 2 mm/sec and 3 mm/sec and depth of cuts are 1mm, 2mm and 3mm) respectively to conduct number of experiments as per the DOE. Taguchi L_9 orthogonal array design was used as to conduct the experiments at various levels.

II. Experimental Setup

2.1. Schematic of machining:

The work piece materials selected for investigation is uni-directional(UD)(+45/-45^0) and bi-directional(BD) (0^0/90^0) glass fiber reinforced polymer composites fabricated by hand layup compression moulding technique of 40%fiber and 60%of polyester resin of 100mmx100mmx10mm dimension. In this study, the experiments are carried out on a conventional universal milling machine incorporated by high speed spindle motor 10Hp to perform slots on work pieces by 10mm diameter solid carbide end mill cutter. Here the machining component forces are (F_x-feed force, F_y-cutting force and F_z-Thrust force, therefore resultant machining force 'F' is obtained by $F = \sqrt{F_x^2 + F_y^2 + F_z^2}$) and readings were obtained by mill tool dynamometer, the work piece is properly fixed in specially designed fixture which is centrally located in mill tool dynamometer. The surface roughness was measured along the cut slot from Mitutoyo profiler the cut-off value and transfer length were set as 0.5mm/sec 5mm while take the centreline average surface roughness of three different places readings are taken to obtain the precision data. Here the spindle speed (rpm), feed (mm/sec) and depth of cut (mm) are controlled input parameters in this investigation. Each experiment was conducted three times and finds the delamination (W_{max}) around the each slot at three places by using travelling microscope with magnification of 200X. The average value is taken as the delamination value by calculation. The properties of GFRP are shown in table 2.1. Various machining process parameters and their levels for run the experiments are shown in table 2.2.

Table 2.1. Properties of UD and Bi-directional GFRP composite laminates

S.NO	Property	Avg. value for UD (+45/-45^0) GFRP	Avg. value for Bi-D (0^0/90^0) GFRP
1	Ultimate Tensile strength (Mpa)	193	282
2	Flexural strength (Mpa)	94	108
3	Rockwell hardness number	55	48

Table 2.2. Control process parameters and their levels

			Levels		
Process Parameters	Units	Notation	1	2	3
Spindle speed	RPM	N	1153	1950	2500
Federate	mm/sec	f	1	2	3
Depth of cut	mm	d	1	2	3

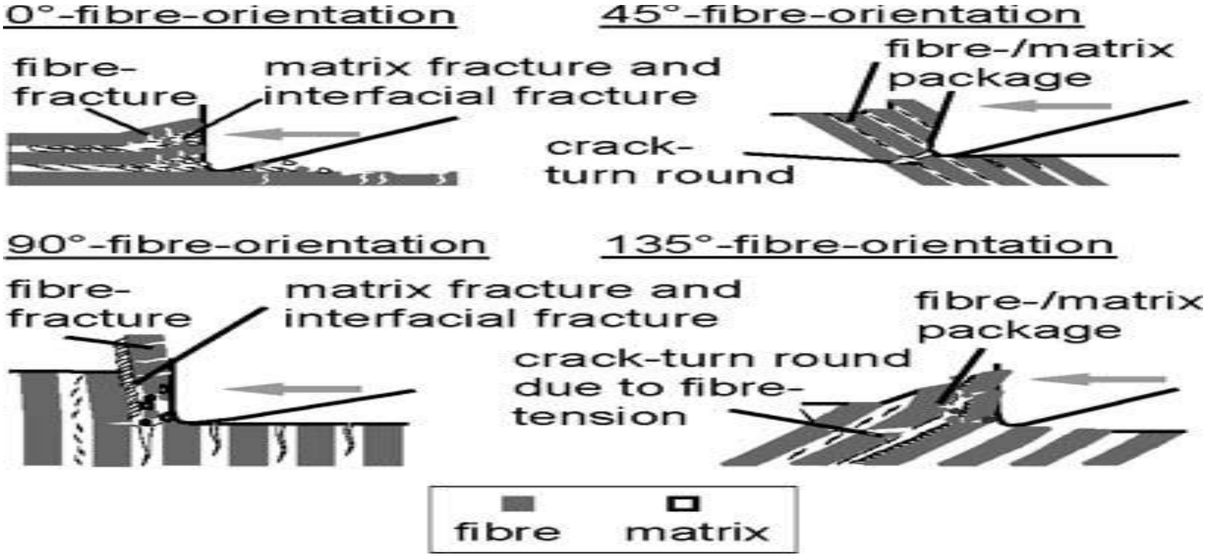
2.2. Taguchi experimental design and selection of parameters:

Extensive and expensive experimentations would typically be required to evaluate the machinability of a material. Hence, in this study, Taguchi DOE technical method was used to design the experimental matrix is systematically plans the experiments according to a specially designed orthogonal array (OA). Here each combination of factors has a balance, in which within a column of the array, each factor has equal number of levels. The unique characteristics of GFRP composites affect their machinability differently to those of the traditional homogenous materials. Further physical properties of fiber reinforcements and the matrix material, fiber orientation angle, fiber types, type of matrix material, fiber volume fraction and environmental conditions greatly influence the machinability of GFRP composites apart from processing parameters which includes cutting speed, feed rate and depth of cut, tool materials and geometries. Such a large number of influencing factors inevitably add to the complexity of experimental investigations. Hence, in this part of work, only machining or processing parameters were considered for the parametric analysis of their significant influence. The three important machining parameters namely feed rate, f; spindle speed, N; and depth of cut, d; that effects the resultant machining force, surface roughness and delamination. The range of machining conditions was selected owing to the importance of industrial applications, within the limit of the machine tool as well as over the range of conditions employed. In the current parametric study could be well performed using the L9 Taguchi OA in which nine experimental runs would be required to complete the array. In the Taguchi analysis, the average value of experimental response and its corresponding signal to noise ratio (S/N) of each run can be calculated to analyze the effects of the machining parameters. However, in this paper, S/N ratio was chosen for the Taguchi analysis because S/N ratio can represents both the average (mean) and variation (standard deviation) of the experimental results. Hence, depending on the qualitative characteristics of the experimental response, the S/N ratio can take up 'the lower the better'.

2.3. Measurement of machining force, Surface roughness and delamination factor:

Forces acted on the cutting tool which can be measured by a mill tool dynamometer with data acquisition system and processed on a personal laptop. The surface roughness was measured with talysurf for knowing the surface quality cutoff value and transfer length were set as 0.5mm/sec 5mm. The computation of the delamination was done by the measurement of the maximum width of damage (W_{max}) was changes from one material to other material, the damage normally allocated by delamination factor (Fd) was resolved. This factor is defined as the quotient between the maximum width of damage (W_{max}), and the width of cut (W). The value of delamination factor (Fd) can be achieved by the following equation: $Fd = (W_{max}/W)$. W_{max} is the maximum width of the damage in mm and 'W' is the width of cut in mm. All the above measurements are repeated three times to check for the consistency

"Fig.''2.1. (a). Machining of GFRP laminate plate is properly fixed in machining center by special designed fixture located on mill tool dynamometer (b). Measurement of delamination damage using Travelling Microscope (c). Measurement of surface roughness by Mitutoyo Talysurf



"Fig.''2.2. Cutting mechanisms for FRP composites [13]

III. Results and Discussion

The results of the milling tests allowed the evaluation of the GFRP composite material manufacture by hand-layup compression moulding technique, uni- directional (UD) (+45/-45^0) and bi-directional (BD) (0^0/90$^{0)}$ glass fibre reinforced plastics using 10mm diameter solid carbide end mill cutter. The Machinability was evaluated for resultant force (F), surface roughness (Ra) and delamination factor (F_d).

3.1. Influence of the cutting parameters on the resultant forces based on S/N Ratio

Table3.1, shows that the results of the resultant force (F), as a function of the cutting parameters for the different fiber orientations. Table3.2, illustrates the results of Taguchi analysis (S/N ratio) of the resultant force in UD and Bi-directional GFRP laminates for solid carbide end mill cutter using the approach of smaller is better . From table3.2, it can be seen that the factor speed is the most significant and the factor feed is the next significant in machining of UD-GFRP laminates. In table 3.2, feed is the most significant and the factor speed is the next significant factor in machining of Bi-D GFRP laminates. This is due to effect of fiber orientation; the cutting forces are gradually increases when the fiber orientation is changes from 45^0 to 90°. The principle of cutting forces is also associated with chip cutting along/ across the fiber ply orientation. Hence we have seen more forces presented while machining of UDGFRP laminates than Bi-D GFRP laminates from this present experimentation.

Table 3.1. The resultant force values obtained on machined surface with different laminates

Exp. No	Spindle Speed (RPM)	Feed (mm/sec)	Doc (mm)	Resultant force for UD GFRP laminate	Resultant force for Bi-D GFRP laminate
1	1150	1	1	16.34	15.59
2	1150	2	2	17.35	16.89
3	1150	3	3	21.34	19.58
4	1950	1	2	19.25	18.57
5	1950	2	3	21.34	19.97
6	1950	3	1	20.16	20.12
7	2500	1	3	20.38	18.66
8	2500	2	1	19.98	17.95
9	2500	3	2	21.37	20.35

Table 3.2. Responses S/N ratio for resultant forces with different GFRP laminates

Exp. No	Speed (RPM)	Feed (mm/sec)	Doc (mm)	S/n ratios for UD GFRP laminate	S/n ratios for Bi-D GFRP laminate
1	1150	1	1	-20.53	-24.75
2	1150	2	2	-21.41	-25.64
3	1150	3	3	-21.55	-25.56
4	1950	1	2	-20.69	-24.88
5	1950	2	3	-21.09	-25.21
6	1950	3	1	-21.70	-25.84
7	2500	1	3	-20.76	-24.82
8	2500	2	1	-20.99	-25.37
9	2500	3	2	-21.74	-25.75

3.2. Influence of the cutting parameters on the surface roughness based on S/N Ratio

Table 3.3, shows the results of the surface roughness (Ra) as a function of the cutting parameters for machining of different ply orientation of laminates. Table6 illustrates the results of Taguchi analysis (S/N ratio) of the surface roughness in the GFRP laminate for solid carbide end mill cutter using the approach of smaller is better. From table 3.4, it can be seen that the factor feed rate is the most significant and the depth of cut is the next significant in significant in machining of UD and Bi-D GFRP laminates. The experimental results indicate that high surface roughness is obtained for low fiber orientation angle (45^0) than the high fiber orientation angle (90°) as well as feed rate is increases, the interaction between cutting tool and work piece decreases, thus steadily reduces the surface roughness. It is evident that feed rate is the significant factor which influence on surface roughness fallowed by depth of cut [14].

Table 3.3. The surface roughness values obtained by machined surface with different laminates

Exp. No	Spindle Speed (RPM)	Feed (mm/sec)	Doc (mm)	Surface finish for UD GFRP laminate	Surface finish for Bi-D GFRP laminate
1	1150	1	1	2.35	2.14
2	1150	2	2	2.21	2.04
3	1150	3	3	2.16	1.97
4	1950	1	2	2.06	1.96
5	1950	2	3	2.25	2.08
6	1950	3	1	1.98	1.79
7	2500	1	3	2.37	2.10
8	2500	2	1	1.96	1.79
9	2500	3	2	1.89	1.87

Table 3.4. Responses S/N ratio for surface roughness with different GFRP laminates

Exp. No	Speed (RPM)	Feed (mm/sec)	Doc (mm)	S/n ratios for UD GFRP laminate	S/n ratios for Bi-D GFRP laminate
1	1150	1	2	-6.999	-6.230
2	1150	2	2	-6.418	-5.754
3	1150	3	3	-6.290	-5.646
4	1950	1	2	-7.065	-6.299
5	1950	2	3	-6.592	-5.870
6	1950	3	1	-6.051	-5.461
7	2500	1	3	-6.400	-5.574
8	2500	2	2	-6.231	-5.825
9	2500	3	1	-7.076	-6.232

3.3. Influence of the cutting parameters on the delamination factor based on S/N Ratio:

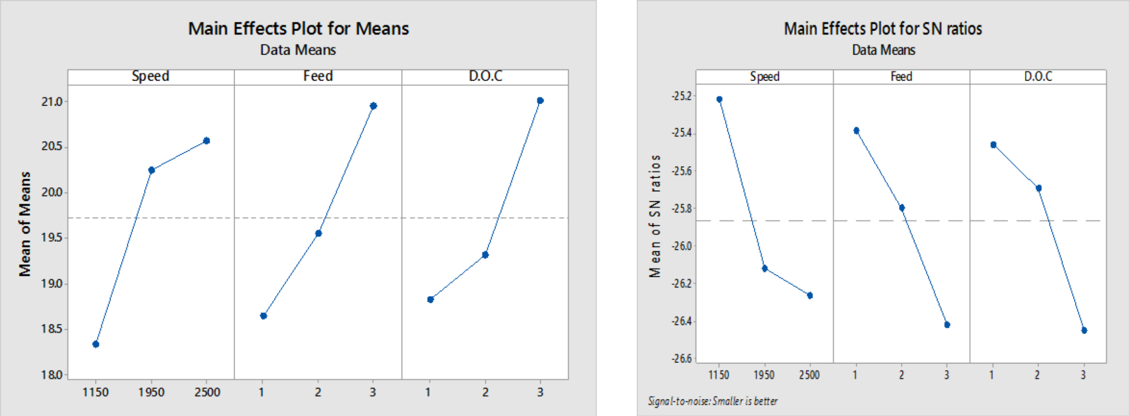
Table 3.5, shows the results of the delamination factor (Fd) as a function of the cutting parameters for machining of different ply orientation of laminates. Table 3.6, illustrates the results of Taguchi analysis (S/N ration) of the delamination factor in the GFRP laminate for solid carbide end mill cutter using the approach of smaller is better. From the response table 3.6, it can be seen that the factor depth of cut is the most significant and the feed rate is the next significant in machining of UD and Bi-D GFRP laminates. From the analysis above, the depth of cut are seen to make the largest contribution to the overall performance. This is due to, when the mill cutter fed across the fiber orientation (+45/-45^0) it squeeze dominated fiber failure will occur in machined slot.. When increasing the depth of cut, more irregularities of machined slot will appear on surface in depth of laminate, apart from due to high friction which is created between tool and work piece, the fiber peel up and thermal damage of matrix material will takes place with depth of penetration of cutting tool. From the results of tables and figures 3.1 and 3.2, which shows that better surface finish and less delamination factor was arrived while machinining of bi-directional GFRP laminates, because the mill cutter edges fed along the direction of fiber orientation (0^0/ 90^0), for this reason less rubbing action created between tool edge and fiber ply. But when machining of UD GFRP composite laminates the cutting tool which past across the angle of fiber ply (+45/-45^0), due to this more feed force was acted in this direction, consequently increasing the friction between tool and work piece, as well at higher feed rates leads to increasing the cutting forces, therefore chances to damages on work piece and enormously increasing the surface roughness. Hence from this investigation we can say that type of fiber orientation angle is most significant factor which influenced on cutting process parameters in milling of different orientation angles of UD-GFRP and Bi-directional GFRP composite laminates.

Table 3.5. The delamination factor values obtained on machined surface with different laminates

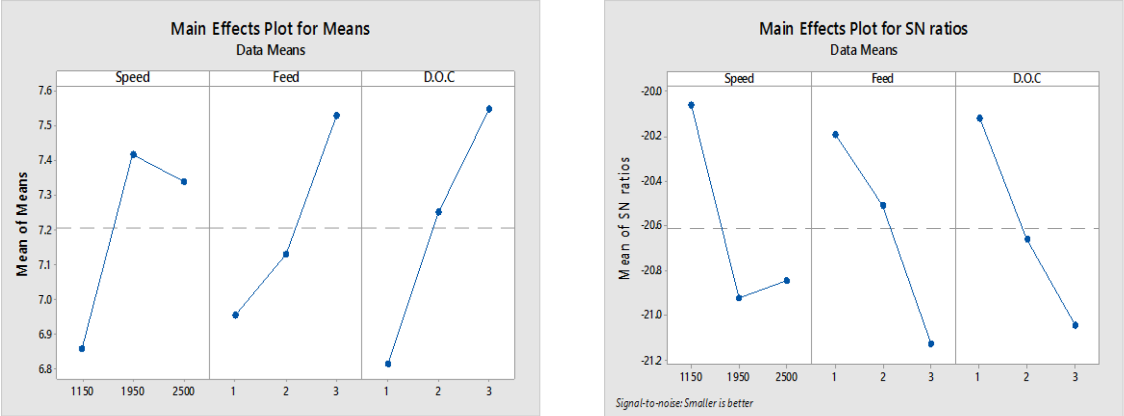
Exp. No	Spindle Speed (RPM)	Feed (mm/sec)	Doc (mm)	Delamination factor for UD GFRP laminate	Delamination factor for Bi-D GFRP laminate
1	1150	1	1	1.102	1.122
2	1150	2	2	1.235	1.213
3	1150	3	3	1.246	1.195
4	1950	1	2	1.324	1.270
5	1950	2	3	1.301	1.211
6	1950	3	1	1.024	1.043
7	2500	1	3	1.203	1.196
8	2500	2	1	1.103	1.042
9	2500	3	2	1.112	1.110

Table 3.6. Responses S/N ratio for delamination factor with different GFRP laminates

Exp. No	Speed (RPM)	Feed (mm/sec)	Doc (mm)	S/n ratios for UD GFRP laminate	S/n ratios for Bi-D GFRP laminate
1	1150	1	1	-1.5291	-1.3837
2	1150	2	2	-1.6440	-1.3575
3	1150	3	3	-1.1284	-0.9194
4	1950	1	2	-1.6289	-1.5238
5	1950	2	3	-1.6587	-1.2174
6	1950	3	1	-1.0139	-0.9194
7	2500	1	3	-0.6348	-0.5552
8	2500	2	1	-1.7321	-1.5461
9	2500	3	2	-1.9346	-1.5592



“Fig.’’3.1. Illustration of main effect plots and responses of UD GFRP composite laminate



“Fig.’’3.2. Illustration of main effect plots and responses of bi-directional GFRP composite laminate

IV. Conclusions

An experimental approach to the evaluation of surface quality caused by various GFRP composite laminates using design of experiments was studied. The results are summarized as follows:

1. For UD GFRP laminates, it was possible to obtain surfaces between 1.89 µm to 2.37µm of surface roughness (Ra), as function of cutting parameters used which is suitable for most of the industrial applications.
2. For bi-directional laminates surfaces obtain between 1.79 µm to 2.10 µm of surface roughness (Ra), as the function of cutting parameters used, which is lower when compared to machined UD GFRP laminates.
3. For machined bi-directional GFRP composite material has got less damage factor than the UD GFRP composite material i.e. the delaminating factor is smaller.
4. Experiments revealed that for machining of both uni- directional (UD) and bi-directional (BD) (0^{0}/90$^{0)}$ glass fibre reinforced plastics from surface roughness point of view, the most appropriate optimal parameter in case of end milling is spindle speed at 2500 rpm, feed rate at 3 mm/sec and depth of cut at 2mm.
5. Experiments revealed that for machining of both uni- directional (UD) and bi-directional (BD) (0^{0}/90$^{0)}$ glass fibre reinforced plastics from delamination point of view, the most appropriate optimal parameter in this case of end milling is spindle speed at 1950 rpm, feed rate at 3 mm/sec and depth of cut at 1mm.
6. The feed rate factor is seen to make the largest contribution fallowed by spindle speed and depth of cut to the overall performance in all the cases

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