6.1. INTRODUCTION

With the present day level of machining technique in which historically, a number of materials used as work material due to the advent of the air craft and space research oriented industries and their engineering applications, the study and control of cutting forces do play an important role. Further the cutting forces being convenient quantitative parameter that can be used in a number of occasions to infer about certain other quantitative or qualitative parameters in machining which cannot be readily measured. Thus it is possible to have adaptive control system incorporating wear sensing through forces, optimizing the productivity by monitoring the forces, providing new concept of machinability based upon cutting force monitoring besides power monitoring through the use of cutting forces.

The anisotropy, non homogeneity and abrasive nature of FRP composite materials provides some problems like excessive tool wear, poor surface finish, delamination, fiber pullout and excessive cutting forces due to improper selection of cutting and tool parameters. In the present chapter, attention has been devoted on experimental study of the orthogonal cutting mechanism in the turning of bi-directional Glass Fiber Reinforced Polymer (GFRP) composite specimens made of E-glass fiber and vinyl ester resin under various cutting conditions. The single edged High Speed Steel (M42)
and Carbide tipped (K20) tools were used for the study of orthogonal machining at varying tool and cutting parameters. A strain gauge type tool dynamometer was used to record the cutting (tangential force) force $F_c$ and feed (thrust force) force $F_t$. The force fluctuations at different cutting conditions were recorded using storage type oscilloscope. Wear profiles were plotted after each cut for a given set of cutting condition using optical profile projector.

The experimental results revealed that the cutting speeds 360 and 450 rpm performed well on the HSS tool with geometry $5^\circ$ rake angle and $17^\circ$ relief angle. However the machining performance of Carbide tipped tool was excellent when compared to the HSS tool. The tool geometry of the carbide tipped tool $5^\circ$ rake angle and $10^\circ$ relief angle performed well at 450 rpm cutting speed.

6.2. OBJECTIVES

- Preparation of hollow cylindrical unidirectional and bi-directional GFRP specimens using filament-winding process.
- To establish an experimental set up to record cutting forces, force fluctuations and tool wear during machining.
- To perform face-turning operation on the above specimen at various cutting conditions using HSS and Carbide tipped tool.
- To record the cutting and feed force values and force fluctuation profiles for various situations.
❖ To measure the flank wear progress and plot the flank wear profiles after each cut for various cutting conditions.
❖ Identifying the optimum tool and cutting parameters giving minimum cutting forces, tool wear and force fluctuations.
❖ Comparing the experimental results with the mathematical model and the results of previous works.

6.3.EXPERIMENTAL DETAILS

6.3.1 Specimen Preparation

6.3.1.1 Filament winding for BGFRP specimen

In filament winding process the mandrel rotates continuously and the resin bath reciprocates in the guide ways. The fibers coming out from the reel are allowed to dip in the resin contained in the resin bath. The resin bath is arranged to traverse along the length of a mandrel over which the impregnated fibers are wound. The traversing speed of the resin bath depends upon the angle of winding and the rotational speed of the mandrel. Changing the relative speed between the mandrel and resin bath can vary the winding angle. The winding tension is created by the resin bath. Rollers are used in the resin bath to guide the filaments effectively into the resin. The machine has a spindle and a carriage over which the resin bath is placed. A DC motor runs the spindle and different speeds are achieved through a variator. The dwell period at the ends of the mandrel is achieved through a timer, which stops the carriage for a specified period of time. The end position of the carriage is sensed through a limit switch, the actuation of which reverses the motor. The carriage rests on two longitudinally placed cylindrical
beds, by means of roller supports. The carriage is driven by means of a chain drive. The mechanism adapted in the process is illustrated in Fig 6.1.

![Figure 6.1: Mechanism of Filament winding process adapted in fabricating BGFRP pipe specimen](image)

It is observed that the above mechanism is used in most of the commercial industries. Filaments and Windings India Ltd., Kurichi, Coimbatore, presently adapting this process. The bi-directional GFRP pipe specimens for the present investigation were fabricated in the above concern. The cylindrical pipes made of bi-directional GFRP composite are presently used as acid transfer lines. The winding carried out at this concern is the classical helical pattern winding.

In this process the specimens were fabricated in two phases, initially a gel coat of 0.05mm thickness (a mixture of vinyl ester resin and aerosol powder) was used on the outer surface of the mandrel for the easy removal of the specimen. The first phase was carried out by hand lay-up process in which, to get the inner smooth surface to ensure the free flow, a chopped strand mat (CSM 450) with vinyl ester resin was used in two stages to attain
the thickness of 4mm. The second phase is used to give strength to the FRP pipe, which consists of glass fiber roving manufactured by filament winding process. The fibers were wounded at 57° to 58° fiber-orientation on either direction. Cobalt and MEKP (Methyl Ethyl Ketone Peroxide) were used as accelerator and catalyst respectively for both the phases. The pipes fabricated were of 100mm diameter and 8mm thickness.

6.3.1.2 Filament winding for UGFRP pipe specimen
It is experienced that, the above process posses some limitations, such as the process is highly expensive and find difficulty in winding angle control. In order to circumvent these limitations, an existing HMT CNC LATHE ECONO-CNC 26 (HINUMERIK 2000T) has been used for this purpose. The normal range of spindle speed required for filament winding should be 10 to 30 rpm [85,86]. As in conventional lathe the minimum available spindle speed is 40 rpm and also the corresponding carriage speed for different winding angles is not available, it was decided to use the CNC machine for winding, so that the desired low rpm and very high carriage speeds can be achieved. The combination of these two can be used to produce components with any desired angle. The machine was programmed according to the winding angle required.

The device utilizes few accessories like resin bath, mandrel and filament guide. The resin bath is one of the important accessories used in filament winding process. It consists of a hollow tube like structure to hold the resin curing agent mixture with a number of rollers mounted on shafts. These rollers guide the incoming fiber strands and also they control the resin
percentage by squeezing excess amount of resin from the filament strands. The resin bath should possess the following characteristics [85,86].

- The resin bath should be capable of guiding the filament strands properly through it.
- It should ensure the uniform dipping of the fiber in the resin.
- Suitable provision should be made to control the percentage of resin.
- The resin bath should have a smooth surface at the filament passage area so that no damage should be caused to the filaments passing through it.

The mandrel is a mild steel pipe, over which the filaments are required to wound. The mandrel should be prepared prior to the beginning of the winding process. For easy removal of the specimen after cure the steel pipe mandrel is covered with plastic sheet (1mm) with the help of cellophane tape. The mandrel is also provided with taper pins circumferentially on the two edges of it, so that unidirectional winding of filaments is made possible. These pins help in orienting the fiber in a parallel direction when the carriage comes to the end positions and reverse the direction. The filament guide is a circular ring, which is attached to the carriage of the CNC lathe. This guide helps in controlling the filament winding at the required angle. The diameter of the ring should be as small as possible so as to reduce the error caused in the orientation of the fiber.

6.3.1.2.1 Winding Process

The important aspect to be considered during the winding of unidirectional filaments is the proper control of the winding angle. The winding angle is
controlled through varying the rotational speed of the spindle and feed rate of the carriage. The relation between the feed and rpm is determined as follows. In the triangle shown in Fig 6.2, for one revolution of the spindle and the corresponding angle required, the pitch can be calculated using the pythagorus theorem. This pitch is the distance that the carriage should travel for one rotation of the spindle.

\[ \tan \theta = \text{Pitch} / \pi d \]

For example if the diameter of the mandrel is 10cm and the required angle of winding is 45° then the pitch of the carriage is calculated as follows:

\[ \tan 45^\circ = \frac{\text{Pitch}}{\pi \times 10} \quad \text{ie} \quad \text{Pitch} = \tan 45^\circ \times 31.4 = 31.4 \text{ cm} \]

Similarly the feed and speed of the spindle calculated for various winding angles are listed below. The diameter and speed of the mandrel are 60 mm & 15 rpm.

<table>
<thead>
<tr>
<th>Winding angle in degrees</th>
<th>Carriage Speed cm/rev</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>104.84</td>
</tr>
<tr>
<td>40</td>
<td>158.16</td>
</tr>
<tr>
<td>50</td>
<td>224.64</td>
</tr>
<tr>
<td>60</td>
<td>326.52</td>
</tr>
<tr>
<td>70</td>
<td>517.92</td>
</tr>
</tbody>
</table>

The commercially available epoxy resin of suitable grade is taken and the required amount of curing agent is added to the resin and mixed thoroughly. The quantity of the resin taken is decided by the percentage of resin required in the FRP pipe. The percentage of the resin required, in turn
depends on the application of the composite pipe. The curing agent should be added with due care, since too high quantity of it will lead to a very quick setting of the resin, even before the winding is completed and too low an amount will delay the setting for days. The supplier will specify the optimum amount of the curing agent to be added. After the resin and the curing agent are mixed thoroughly, the mixture is poured in to the resin bath. The process adapted to fabricate the unidirectional GFRP pipe specimen is illustrated in Fig.6.3.

After the initial arrangements, the roving are allowed to pass through an elevated stand holder in to the resin bath. As the strands move through the bath they get dipped in the resin. The rollers in the resin bath guides the incoming fiber strands and also controls the resin percentage by squeezing excess amount of resin from the filament. Finally the strands will pass through
the circular guide provided at the carriage and wound around the mandrel. As soon as the carriage reaches to the extreme position of the mandrel, a dwell period is given for the carriage for the filaments to get oriented. When the carriage starts to move reverse, the direction of rotation of the spindle gets reversed and the filaments gets locked by the taper pins provided at the ends, so that the filament does not get unwounded. The number of passes of the carriage is programmed according to the thickness of the pipe required. Suitable provision may be made to drain the excess resin dripped off from the mandrel. Once the required wall thickness is achieved the winding is stopped and the mandrel is removed from the chuck of the machine. The mandrel is placed in a suitable position and the taper pins are removed. Then winding is allowed to set for the stipulated period of time. After the resin is set, the winding along with plastic sheet is removed from the mandrel. Any excess resin on the surface of the mandrel is cleaned off. The specimens prepared by filament winding process are shown in Fig.6.4.

Figure 6.4 Specimens fabricated by filament winding process
6.3.1.2.2 Limitations and suggestions

> In the specimen produced, the orientation of the filaments was slightly disturbed. This may be because of larger guiding ring diameter. However this limitation can be avoided by proper design of the guiding ring.

> Occasional errors in the locking of the filaments were observed. As the locking was performed manually, these errors can be prevented if automatic locking facility is provided.

> Further the resin, which drips during the winding process should be suitably drained in to a collecting vessel in order to maintain the accurate fiber/resin percentage. Proper arrangement should be made to drain the excess resin to the resin bath

6.3.2 Parameter Selection

The predominant parameters considered for the present machinability study on bi-directional GFRP composite material are the cutting speed, tool angles and tool material. High Speed Steel and Carbide tipped tools with straight cutting edge were used for machining. Four cutting speeds (62.8, 78.4, 113.1 and 141.4 M/min) and four tool rake and relief angle (5°&7°, 5°&17°, 10°&7° and 10°&17°) combination respectively were selected for HSS tool and 10° & 5° rake and relief angle combination respectively for Carbide tipped tool. The machining was carried out in dry condition. The readings were recorded for each 10mm length of cut. The depth of cut of 4mm and feed of 0.06mm/rev were maintained constant. The cutting and tool parameters selected for this analysis are within the range prescribed [80,81].
6.3.3 Experimental Set up

Fig. 6.5 (a) and (b) illustrates the block diagram of the experimental set-up and the photograph showing turning experimentation respectively. The set-up was arranged based on experimental technique followed for metals [87].
6.4 RESULTS AND DISCUSSION

6.4.1 Tool forces

The machinability index of engineering material is evaluated by different parameters; most widely used being cutting force, surface finish and tool-wear. Because of the intrinsic weakness of the resin, even relatively low cutting forces can result in unacceptable delamination and matrix cracking in the work material. In addition, thermal spikes arising as a consequence of too high cutting speeds often cause resin degradation. Finally, the highly abrasive nature of glass fiber leads to rapid wear of conventional tools, which in turn gives rise to an increase in cutting forces and the extent of damage in the work piece. In the present experimental analysis face turning was performed on FRP pipe specimens, cutting forces at various cutting conditions were recorded from strain gauge type tool dynamometer. The force fluctuation profiles in the form of wave formats were plotted using storage type oscilloscope (TEKTRONICS). The tool-wear profiles after machining at each cutting condition were plotted by optical profile projector (BATYS). The dynamometer was directly linked to the laser printer through the storage type oscilloscope (TEKTRONICS) to record the graphical output for cutting force fluctuation during different cutting condition. The BATYS optical profile projector was used to determine the tool flank wear. The wear profiles for different cutting conditions were plotted on plain sheets.
oscilloscope. The influence of cutting speed, tool angle and tool material on cutting and feed force values has been analysed.

6.4.1.1 Influence of Cutting Speed on cutting forces
Fig 6.6 and 6.7 illustrates the effect of cutting speed on cutting force \((F_c)\) and feed force \((F_t)\) values for 5° and 10° tool rake angles respectively. Results revealed that, for all cutting conditions both cutting and feed force values have been decreased with the increase of cutting speed up to 113.1 m/min, after which a slight increase in cutting and feed force values was observed. At lower cutting speeds the tools require higher cutting forces to remove the chip material. However at higher cutting speeds the tool worn out quickly requires higher cutting forces.

![Graphs showing the effect of cutting speed on tool forces](image)

Figure 6.6 (a & b) Effect of cutting speed on tool force for varied tool relief angle at 5° rake angle
Highest cutting and feed force values 39 and 26 Kgf respectively were observed on tools of $5^\circ \times 7^\circ$ and $10^\circ \times 7^\circ$ rake and relief angle combination respectively at cutting speed 62.8 m/min on HSS tools. Large difference in cutting to feed force values was observed at lower cutting speeds, however this variation was reduced at higher cutting speeds. At 113.1 m/min for all tool angle combinations the cutting and feed force values are almost closer with minimum difference in force values (Fc 14 to 17 Kgf and Ft 12 to 17 Kgf). Maximum difference in feed (Ft 10 to Fc 32 Kgf) to cutting force value was observed at 62.8 m/min at $\alpha =10^\circ$ and $\gamma =17^\circ$. Cutting speed 113.1 m/min has shown favourable results for all tool angle combination.

![Graph](image-url)

Figure 6.7 (a&b) Effect of cutting speed on tool force for varied tool relief angle at $10^\circ$ rake angle
6.4.1.2 Influence of tool angles on cutting force values

The tool geometry has got a predominant role in effecting the cutting and feed force values. The correlation between the tool angles v/s the cutting and feed force values recorded at 62.8m/min cutting speed are illustrated in Fig 6.8. Maximum cutting force and feed force values were observed at 5°x17° and 10°x7° tool rake and relief angle combination respectively. Results revealed that there is an increase in cutting force with the increase of relief angle and decrease of rake angle. This is because of high compression on tool face at higher tool relief angle and lower rake angle.

![Figure 6.8 (a) Effect of tool angles on cutting and feed force values at v = 62.8m/min](image)

![Figure 6.8 (b) Correlation between experimental and analytical results](image)
Maximum and minimum feed force (Ft) values were observed at 10° x 7° and 10°x17° rake and relief angle combination respectively. This indicates the decrease in feed force value with the increase of relief angle at a constant rake angle. However the variation in rake angle on feed force values has shown some typical results at two relief angles. The feed force was increased with the increase of rake angle at 7°-relief angle combination, however it is decreased with the increase of rake angle at 17°-relief angle combination. The variation in cutting force values with the tool rake angles has been depicted in fig 6.8 (a). It is seen that the cutting forces are decreasing with the increase of tool rake angle. This is because of less compression on tool face at higher tool rake angles.

The correlation between experimental and the modified Merchant's model results are illustrated in fig 6.8 (b). The modification of the Merchant's equation has been derived in chapter.7. Though the experiments have been conducted for only two tool angle combinations, the intermediate values from the polynomial equations of experimental results were used to compare with the mathematical model. The experimental results have shown good agreement with the modified Merchant's model.

Fig 6.9 illustrates the relationship between the cutting and feed force values v/s cutting speeds and tool angles. These graphs examine the variation of cutting and feed force values with respect to tool angles at a given cutting speed. It is clear from the figure that for most of the tool angles combinations the cutting and feed forces were decreased with the increase of cutting speed up to 113.1m/min and a rapid increase was observed after this
speed. At cutting speeds 62.8 and 78.4 m/min maximum cutting force was observed at $5^\circ \alpha 7^\circ \gamma$ tool angle combinations and minimum cutting force was observed at $10^\circ \alpha 7^\circ \gamma$ tool angle combination, probably this may be due to increase in tool rake angle. Increase in tool rake angle decreased the cutting forces at lower cutting speeds. At 113.1 m/min the cutting force values for all tool angle combinations were observed to be very nearer to each other, ranging from 15 to 18 Kgf. A slight deviation was observed after this speed for most of the tool angle combinations. Though there is deviation towards increase in feed force values at 113.1 m/min for all tool angle combinations, the trend of feed force variation up to this speed is different for different tool angle combination. At 62.8 m/min the tools with $5^\circ \alpha 7^\circ \gamma$ and $10^\circ \alpha 7^\circ \gamma$ combination worked with maximum feed force, almost with the same magnitude. A rapid decrease at 78.4 m/min and gradual increase in feed force after this speed was observed.

The change in rake angle on tools with $5^\circ \alpha 7^\circ \gamma$ and $10^\circ \alpha 7^\circ \gamma$ combinations did not have shown any influence on the feed force values. Tool combination $10^\circ \alpha 17^\circ \gamma$ take minimum feed force value while cutting at 62.8 m/min. No much variation in feed force values were observed at 141.4 m/min for all tool angle combinations. Tool with $10^\circ \alpha 17^\circ \gamma$ combination works with minimum feed forces at lower cutting speeds and tool with $5^\circ \alpha 17^\circ \gamma$ combination works with minimum cutting forces at higher cutting speeds respectively. A specific relation is found to exist between the tool angles and cutting speed on cutting and feed force values.
6.4.1.3 Force fluctuation

The force fluctuation profiles in the form of waves have been recorded using storage type oscilloscope, which is linked to the dynamometer to receive the input. Typical force fluctuation profiles obtained during the face turning of BGFRP pipe specimen at cutting speeds 62.8 and 141.4 m/min using HSS tool, with various tool angles combinations at a constant depth of cut are shown in fig 6.10. A relatively high degree of fluctuation in the cutting force was noted at 5° x 7°-rake and relief angle combination at 62.8 m/min cutting speed. Minimum feed force fluctuations were observed for all tool angle combinations. The tool with 10° x 7°-rake and relief angle combination at

![Graph showing correlation between tool forces, cutting speed, and tool angles.](figure6.9.png)

Figure 6.9 Correlation between tool forces, cutting speed and tool angles.
141.1 m/min cutting speed has shown relatively minimum fluctuation on cutting force.

<table>
<thead>
<tr>
<th>Cutting Speed M/min</th>
<th>α = 5°</th>
<th>α = 5°</th>
<th>α = 10°</th>
<th>α = 10°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Y = 7°</td>
<td>Y = 17°</td>
<td>Y = 7°</td>
<td>Y = 17°</td>
</tr>
<tr>
<td>62.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ft</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fc</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>141.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ft</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.10 Cutting and feed force fluctuations for various tool angle combinations at minimum and maximum cutting speed.

6.4.1.4 Effect of tool material on cutting forces.

HSS and Carbide tipped tools were used to machine the pipe specimen at various cutting conditions. Fig 6.11 illustrates the trend showing the influence of tool material on cutting and feed force values. The trend of both the tool materials is appeared to be similar on cutting and feed force values. However the degree of the influence on HSS tool is observed to be high when compared to the carbide tipped tool. The cutting force values were ranging from 15 to 30 Kgf for HSS tool and 7 to 24 Kgf for Carbide tipped tool for approximately similar tool angle combination. Both the tools worked with
higher cutting and feed force values at lower cutting speeds. However the cutting and feed force values were deviated after 113.4 and 78.2 m/min cutting speeds respectively. The slow advancement of the tool requires higher cutting force to remove the chip material. The early wear of cutting tools at higher cutting speed cause the cutting tool to work at higher cutting force, because of which a slight deviation of cutting and feed forces after 113.4 and 78.2 m/min cutting speeds respectively was observed.

![Graph 1](image1.png)

**Figure 6.11 (a) & (b) Influence of tool material on cutting and feed force values.**

The feed force values were ranging from 14 to 26 Kgf for HSS tool and 0 to 10 Kgf for Carbide tipped tool for approximately similar tool angle combination. The trend of feed force variation for HSS and carbide tipped tool
was appeared to be similar up to 113.1 m/min, however it is seen that the tool works with zero feed force at 141.4 m/min cutting speed.

The overall results have indicated that the carbide tipped tool performed well at all cutting condition compared to the HSS tool. However the machining performance of HSS tool was also found to be good at certain optimum cutting conditions. HSS tools can be successfully used on GFRP composites with optimum cutting parameters. The curves plotted to show the effect of tool material on the cutting and feed force values have shown the perfect third degree polynomial. The statistical curve fit for the third order polynomials obtained from the plots to evaluate the cutting and feed force values for different cutting speeds using HSS and carbide tipped tools are given below. Here y is the cutting force and x is the coded variable for cutting speed.

<table>
<thead>
<tr>
<th>Tool</th>
<th>Cutting force $F_c$</th>
<th>Feed force $F_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSS</td>
<td>$y = 2.5x^3 - 16.5x^2 + 26x + 18$</td>
<td>$y = -2.6667x^3 + 23.5x - 63.833x + 69$</td>
</tr>
<tr>
<td>Carbide</td>
<td>$y = 1.6667x^3 - 10.5x^2 + 11.833x + 21$</td>
<td>$y = -2.1667x^3 + 17x^2 - 42.833x + 38$</td>
</tr>
</tbody>
</table>

6.4.2 Tool Flank Wear.

The most undesirable yet inherent characteristic of machining processes is wear of the cutting tool. In order to prevent further damage to the machine or the production of a rough surface, the essential part of a machining system in an unmanned factory is the ability to replace worn or damaged tools automatically. Most tools fail either from fracturing or gradual wear. During face turning, as the chip flows over the tool face the highly abrasive GFRP chips wears the tool face and causing a crater wear. Secondly with the tool advancement over the machined surface the rubbing action of tool flank over
the machined surface causes the flank wear. The microscopic observations of the worn tools showed that both the face and flank wear essentially consist of a more and more marked roundness of the tool tip (nose wear) at increased cutting speeds. This feature coincides with what is found in metal cutting, where nose wear is predominant when low cutting speeds are involved. In the present experiments, no crater formation on the tool face was observed, probably because of the formation of powder like chips and the absence of notable thermal effects due to low cutting speeds adopted. Only the tool flank wear with respect to various cutting conditions have been analysed. As the HSS tools are less wear resistant than the carbide tipped tools, the degree of wear on HSS tool appeared to be high compared to carbide tipped tools.

6.4.2.1 Effect of cutting speed on tool flank wear
Fig 6.12 illustrates the influence of cutting speed on tool flank wear for different tool angle combinations. It is observed that for all cutting conditions the tool flank wear has been increased with the increase of cutting speed. However the degree of wear progress with respect to cutting speed was varying. Maximum wear of 0.16mm was observed at 141.4m/min on tool with 10° x 17°-rake and relief angle combination. Minimum flank wear of 0.02 to 0.04mm was observed at 62.8m/min cutting speed. However the flank wear is slightly more rapid for the lower relief angles.

Finally, the fast deterioration of the tool sharpness with the increase of cutting speed is clear from the wear profiles illustrated in Fig.6.13, which emphasize the highly abrasive nature of composite materials and confirm the difficulty of HSS tools to work them, yet exhibiting an industrially acceptable
Fig 6.13 illustrates the wear profiles plotted for various tool angle combinations at each cutting condition. The outer straight line illustrates the initial tool profile. Next curve is the profile of wear for first (least) cutting speed and then the subsequent profiles with the increase of cutting speed were plotted. The innermost profile illustrates the wear at highest cutting speed.

Figure 6.12 (a) and (b) Flank wear v/s cutting speed.

Figure 6.13 (a-d) Flank wear Profiles on HSS tool for various tool angle combinations.
The wear profiles revealed that the increase in cutting speed increased the flank wear, however wear along the cutting edge is not uniform. The variation may be due to variation in cutting speed and tool angle combination.

6.4.2.2 Effect of tool angles on tool flank wear
The flank wear values for four different tool angle combinations at different cutting speeds have been illustrated in Fig 6.12. Results revealed that the decrease in relief angle increased the flank wear. With the decrease of flank (relief) angle the flank surface comes closer to the machined surface, causing more wear on the flank surface of the tool at smaller relief angles. No much variation in flank wear due to the variation in rake angle was observed. Flank wear of 0.14mm and 0.085mm was observed at 7° and 17° relief angle respectively when machined at 141.4m/min cutting speed. Wear profiles have shown different shapes for various tool angle combinations as illustrated in fig 6.13. It is observed from the Fig 6.13 © that there is a large gap between the initial profile plotted before cut and the first profile after cutting speed 62.8m/min. This profile was plotted for 10° and 7° rake and relief angle combination respectively, which indicates that high flank wear exists at smaller relief angle. However the wear profiles does not reveal a clear picture of the rate of wear progress at different cutting conditions.

6.4.2.3 Effect of tool material on tool flank wear
High-speed steel and Carbide tipped tools were used in the present analysis. Though Carbide tipped tools perform well in all respect on FRP materials, it is essential to identify the optimum parameters for better performance of HSS tool to avoid high expenses towards cutting tools. Carbide tools are highly
expensive than HSS tool for large scale machining. Fig 6.14 illustrates the variation of flank wear values with the increase of cutting speed for HSS and Carbide tipped tool. Though the chips produced in case of Carbide tipped tools were of continuous type, the crater wear observed was negligible since the machining was performed for very short length in the present work. No much variation on tool flank wear was observed at 62.8m/min on both the tools. However high variation was observed for the remaining cutting speeds. After 78.54m/min the flank wear was ranging from 0.12 to 0.14 mm for HSS tool, where as it is from 0.025 to 0.055mm for Carbide tipped tool.

Fig 6.15 illustrates the wear profiles plotted on HSS and Carbide tipped tool for approximately similar tool angle combination. A large gap between the initial profile and the wear profile was observed on HSS tool profile. In Carbide tipped tool the wear started near the initial profile line and the profile lines of various cutting conditions overlap each other forming a thin narrow band. The distance between the initial profile to the inner profile is very less for Carbide tipped tool when compared to HSS tool.

![Figure 6.14 Flank wear progress on HSS and Carbide tool with respect to speed.](image)

![Figure 6.15 Profile showing the flank wear progress on HSS and Carbide tools.](image)
6.4.3 Regression model to evaluate flank wear

A 2k factorial design of analysis was used to develop a regression model to evaluate the magnitude and direction of the effect of cutting speed and tool relief angle on tool flank wear. Cutting speed and tool relief angle were considered as the predominant parameters, which have direct effect on the tool flank wear. Flank-wear values at two levels (low and high) of cutting speed and tool relief angle have been considered in the regression model construction. Results revealed that the main effect of cutting speed on tool flank wear was +ve and with higher magnitude than the relief angle. This indicates the increase in cutting speed increases the tool flank wear at higher rate than the relief angle. However the effect of relief angle and interaction effect has shown -ve sign indicating the increase in tool relief angle cause to decrease the tool flank wear, because the increase of relief angle reduces the contact between the tool flank and the machined surface. Fig 6.16 illustrates the comparison of experimental and regression model results. Except at 5° x17° tool angle combination and cutting speed 78.4m/min all the results have shown good agreement with the regression model. The form of regression equation obtained by 2k factorial design is noted below. The interaction effect was also considered in the development of this equation.

\[ W_f = 0.03712 v - 0.001609 \gamma - 0.000268 v \gamma - 0.01928 \]

Where \( W_f \) is the tool flank wear in mms, \( v \) is the cutting speed in m/min and \( \gamma \) is the tool relief angle in degrees. This equation enables to evaluate the tool flank wear at any cutting speed and tool relief angle within the range considered in the present investigation.
Fig 6.16 Correlation between experimental and regression results

Figure 6.17 Surface response with respect to cutting speed and tool relief angle.
Fig 6.17 illustrates the three-dimensional surface response plotted using the above regression equation. Slight curvature in the response surface indicates the interaction effect, the magnitude of combined effect was found slightly higher than the main effect of tool relief angle. The figure helps in identifying the variation in tool flank wear with respect to cutting speed and tool relief angle.

![Figure 6.17](image)

**Figure 6.17** Correlation between tool flank wear, cutting speed and tool relief angle.

Fig 6.18 illustrates the correlation between the tool flank wear with respect to cutting speed and tool relief angle. The regression equation, which was developed using the flank-wear values at high and low levels of speed and relief angle were used to evaluate the wear values at the intermediate tool relief angles also. The intermediate values have shown well proportionality with the end values considered. The curves for all the cutting speeds were observed to be negatively linear with respect to tool relief angle where as the positive linearity was observed on tool flank wear with respect to cutting speed.

![Figure 6.18](image)

**Figure 6.18** Correlation between tool flank wear, cutting speed and tool relief angle.
6.5 OPTIMUM PARAMETERS
The HSS tool with 5° x17° rake and relief angle combination respectively has shown excellent performance at 113.1 m/min cutting speed. Comparatively good surface quality with minimum cutting forces and tolerable tool wear was observed. The cutting and feed force values observed at this cutting condition are 14 and 12Kgf respectively. No crater wear was observed and the cumulative flank wear value was observed to be 0.073mm. The cutting speed 141.4m/min for the same tool angle combination also performs well, however the tool flank wear, the cutting and feed force values (Wf=0.088mm, Fc=15 and Ft=17Kgf) are slightly higher than the values obtained from the previous cutting speed.

The Carbide tipped tool has shown excellent results at all cutting conditions. It is seen that K20 type carbide tool cut the GFRP composite with minimum force. The tool flank wear, cutting and feed force values were very less when compared to the HSS tool. The tool flank wear is ranging from 0.02 to 0.06mm. Minimum flank wear of 0.02mm was observed at 62.8m/min cutting speed. However minimum cutting and feed force values were observed at 141.4 m/min cutting speed with flank wear of 0.054mm. Though the flank wear at 62.8m/min is less compared to 141.4.m/min cutting speed, the tool works with minimum cutting forces and also the wear at 141.4m/min cutting speed is tolerable. The continuous chips produced during the application of carbide tipped tool over the specimen revealed the formation of fine surface.
Some of the experimental results have been compared with the results evaluated by modified Merchant's equation, it is observed that most of the experimental results have shown good agreement with modified Merchant's model. Also most of the results of this experiment support the previously presented model that aims to predict cutting forces and tool wear in the orthogonal cutting of unidirectional composites [53].

6.6 CONCLUSION
The turning experimentation on GFRP pipe specimens to evaluate the tool forces and tool wear for different cutting conditions derived the following conclusions.

♦ The HSS tools gave poor cut on fibers and smooth cut on the matrix. Fluctuation of cutting forces in HSS tools were high compared to the Carbide tipped tools. The surface quality obtained by Carbide tipped tool was found to be good compare to the HSS tools.

♦ Due to -ve fiber orientation in the BGFRP composite; excessive tool wear, fiber pull out and delamination was observed at higher cutting speeds. This can be eliminated by proper design of the FRP composite.

♦ GFRP machined surfaces exhibit poor surface finish due to the fussiness caused by delamination during machining.

♦ In HSS tools the chips produced were of powdered form, no crater wear appears. In carbide tipped tools, though the chips were of continuous form the crater-wear does not appear because of short length of machining.
The flank-wear progresses with the increase of cutting speed, but the wear rate in carbide tipped tool was found to be less when compared to HSS tool.

♦ When cutting speed is increased, the nose-wear in both the tool material grown large in the shape of triangle and its wear rate starts to increase remarkably at a certain speed.

♦ The carbide tipped tools have shown favourable results on FRP machining than HSS tools in many aspects, however the optimum parameters identified for HSS and carbide tipped tools gave better results for the situation considered in this work.

♦ Though HSS tool is less wear resistant it is possible to use HSS tool successfully on FRP material with minimum tool wear and cutting forces by incorporating the optimum design parameters along with cutting and tool parameters. The design parameter includes fiber material, fiber orientation and fiber volume.

The results of this experimental programme also support a previously presented model that aims to predict cutting forces in the orthogonal cutting of unidirectional composites.