Theoretical and Experimental Study of Cutting Mechanics of Graphite Fiber Reinforced Preimpregnated Composite (Prepreg) and The Effect of Tool Geometry on Cutting Quality and Fiber Deflection

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Theoretical and Experimental Study of Cutting Mechanics of Graphite Fiber Reinforced Pre-impregnated Composite (Prepreg) and The Effect of Tool Geometry on Cutting Quality and Fiber Deflection

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Abstract

Graphite fiber reinforced composites are becoming strategic materials in aerospace and aerocraft industry due to their high strength to weight ratio. This research work deals with the theoretical and experimental analysis of cutting unidirectional, cross-ply and woven composite prepregs. The effect of cutter-geometry on the prepreg cutting quality as well as fiber deflection is also considered.

The experimental work has been performed using a modified cutting machine, commercially used for sign cutting. The effects of cutting parameters of this sign-cutting machine on cutting quality have been also investigated.

Moreover, experiments have been carried out by hand to investigate the fibre deflection during and after the cutting under different conditions for unidirectional, cross ply and woven prepregs. The effects of fibre deflection on the sample strength were evaluated using Taguchi method.

The mathematical model to express the curvature of fibre deflection was formulated.

Results also show that the cutting mechanism of prepreg is essentially a material failure

due to bending-induced fracture, and also due to shearing and compressive stresses in which the prepreg resin is ploughed and the reinforced fibres of prepreg are cracked . Results indicate that optimal cutting quality of composite prepreg is obtained by applying concentrated cutting force with small cutting angle α. Further work, however, is required to obtain the optimal cutting force and optimal knife-geometry. Similar to metal-cutting processes, this information can be very useful for prepreg cutting machine builder.

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Nomenclature

A	Area of cross section of fiber
a_{ij}	In-plane compliance of laminate
CFRP	Carbon fibre reinforced plastic
C.F.	Correction Factor
EDC	Electrical discharge cutting
E_f	Modulus of fiber
E_m	Modulus of resin
Ex	Longitudinal Young's modulus of laminate made of NCT-301 prepreg
Ey	Transverse Young's modulus of laminate made of NCT-301 prepreg
Es	Shear modulus of laminate made of NCT-301 prepreg
EI_f	Flexural rigidity of fiber boundles
f_t	Total degree of freedom
f_A	Degree of freedom for factor A
f_B	Degree of freedom for factor B
f_C	Degree of freedom for factor C
f_e	Degree of freedom for error factor e
F	Cutting force
F_A	F-ratio for factor A

F_B	F-ratio for factor B
F_C	F-ratio for factor C
F_t	Cutting force component along the knife edge
F_n	Cutting force component perpendicular to the knife edge
F_1	Cutting force perpendicular to the cutting direction
F_2	Cutting force along the cutting direction
FRP	Fibre reinforced plastic
GFRP	Glass fibre reinforced plastic
G_{ij} ,G_i	Strength parameters in strain space
HSS	High speed steel
$H_{ij}^{(\theta)}$, $H_i^{(\theta)}$	Strength parameters of the θ - degree ply in a laminate
k	Elastic modulus of foundation
KFRP	Kevlar fibre reinforced plastic
l	Contacting length between knife and fiber
LBC	Laser beam cutting
n	Total number of experiments
N_i	Stress resultant, i = 1,2,6
P_A	Percentage contribution for factor A
P_B	Percentage contribution for factor B
P_C	Percentage contribution for factor C
P_e	Percentage contribution for error factor e
PCD	Polycrystalline diamond

PREPREG	Pre-impregnated composite
r_1	Primary radius of knife tip
r_2	Primary radius of knife tip
R	Radius of fiber bundles
R_z	Ten-point height of roughness
R_y	Maximum peak-to-valley roughness height
$R^{(\theta)}$	Strength ratio of the θ ply orientation
S	Shear strength of laminate made of NCT-301 prepreg
S_A	Sum of squares for factor A
S_B	Sum of squares for factor B
S_C	Sum of squares for factor C
S_e	Sum of squares for error factor e
S_T	Total sum of squares
T	Total of all experimental results
V_A	Mean square (variance) for factor A
V_B	Mean square (variance) for factor B
V_C	Mean square (variance) for factor C
V_e	Mean square (variance) for error factor e
V_f	Volume fraction of fiber
V_m	Volume fraction of resin
WJC	Water jet cutting
Y	Laminate strength

Y_t	Transverse tensile strength of laminate made of NCT-301 prepreg
Y_c	Transverse compressive strength of laminate made of NCT-301 prepreg
α	Primary knife angle
β	Secondary knife angle
γ	rake angle of tool in metal cutting
δ	Cutting direction to fibre orientation
ε	friction angle in metal cutting
σ	Normal stress
σ_x	Tensile stress along fiber
σ_y	Compressive stress perpendicular to fiber
σ_m	Ultimate stress
σ_{ut}	Ultimate strength of the material in tension
σ_{uc}	Ultimate strength of the material in compression
τ	Shear stress along the cross section of fiber
υ	Poisson's ratio
ϕ	shear angle in metal cutting
ψ	angle for two-cut

CHAPTER 1

INTRODUCTION

1.1 General

A composite material can be defined as a combined material created by the synthetic assembly of two or more components - selected filler or reinforcing agent and a compatible matrix binder (a resin) - in order to obtain specific characteristics and properties.

Advanced composite materials are defined as polymer, metal, or ceramic matrix composite material systems in which the reinforcement is composed of high strength, high modulus continuous fibre. The reinforcement may also be discontinuous in form such as chopped fibres, whiskers, particle dispersion or combination of any of these forms in polymer, metal, and ceramic matrix materials.

In many ways, fibre reinforced polymer composites are the most important class of all advanced composites because they offer a combination of strength and stiffness properties quite superior to similar properties of conventional metallic materials. Almost all high-strength/high stiffness materials fail because of the propagation of flaws. A fibre of such a material is inherently stronger than the bulk form because the number of flaws is limited by the small size of the fibre.

The composite industry employs many reinforcing agent-resin combinations to affect a diversity of performance and cost characteristics. These components are most frequently combined in two forms: the layered form or the moulded form. Many of the properties of the resulting composites are superior to those of components. Although it is composed of several different materials, the composite itself behaves as a single material.

Composite materials provide the designer, fabricator, and consumer with sufficient flexibility to meet the demands presented by different environments (heat and humidity) as well as any other special requirements. Thus, they totally eliminate the crippling necessity often faced by designer of restricting the performance requirements of designs to traditional experience. The goal in creating a composite is to combine similar or dissimilar materials in order to develop specific properties that are related to desired characteristics. Since composites can be designed to provide an almost unlimited selection of characteristics, they are utilized in practically all industries. Composites are used to produce a variety of economical, efficient, and sophisticated items, ranging from toys and tennis rackets to aerospace craft and automobile. [1],[2]

In summary, the major advantages of composites over the traditional material are as follows:

1. low weight;
2. high stiffness and high strength;
3. high corrosion resistance;

4. good fatigue resistance.

As new composite materials with unique properties are being developed, the optimization of their processing technology is eagerly being sought after. The processing can be divided into two categories: primary and secondary. Even if the primary processing of a composite with unique properties is established, it is often the secondary processing that makes an otherwise unique composite unattractive to end-users. This is partly due to the fact that the secondary processing of composites and composite structures has been the least studied in comparison to primary processing. One of the key secondary processes is cutting and machining.

The methods for cutting and machining of composite materials may be classified into two main groups, conventional and unconventional methods.

Conventional cutting and machining methods of composite material involve removing materials by mechanically forcing a cutting edge through a component. Examples of single cutting edge methods are shaping [11], turning [12-15] and boring [5]. Examples of multi cutting edge methods are drilling [4], sawing [5], milling [5], routing [5], and abrasive machining [4,5]. New machining techniques have also been developed such as ultrasonic cutting which involve the use of induced vibrations delivered to the cutting tool.

Recently, other unconventional methods such as laser beam cutting (LBC) [6,8], water jet cutting (WJC) [7,9] and electrical discharge cutting (EDC) have been employed for cutting and machining composites. These unconventional techniques which do not involve mechanical contact with the material are becoming important and sought after because they appear to eliminate tool wear and the dust airborne problem.

Each of the machining methods reported in this study appears to have its own advantages and disadvantages and they compete in certain applications. However, the economical considerations are essential in the selection of the machining method. The advantages of conventional methods are economics, however, their disadvantages are excessive tool wear and poor surface roughness of part. The advantages of unconventional methods are clean cut, however, the drawback of this method is high cost.

Normally, composite materials are hard to cut due to two reasons: the first is related to the discontinuity or the anisotropy of the material, while the second is generally related to the reinforcement material. Typical reinforcement materials, such as glass fibre, graphite fibre and kevlar fibre, are difficult to machine.

There is a wide range of composite materials available, their structures are inhomogeneous and complex. It appears that little few work has been done so far to understand composites inherent machinability, cutting mechanisms, and methods especially suited for advanced composite materials. Thus, it has been rather difficult to machine composites successfully. In addition, the cutting tools are subjected to excessive wear limiting their further use and causing the process of machining to be expensive [3]-[10].

1.2 Literature Review

Composites are non-homogeneous and anisotropic materials, their cutting differs from that of a homogeneous material such as steel. Each type of composite differs in its machining behaviour since the physical and mechanical properties are different. The cutting behaviour of each composite depends also on its fibre form, fibre content and fibre orientation. Therefore, it is not only difficult to analyze the surface formation and tool wear mechanism in cutting composites from the data obtained in metal cutting but also to establish a general theory for cutting composites. Very limited studies on the machining of FRP (Fibre Reinforced Plastics) have been carried out and only a few of papers on machining of FRP composites are available in the literature.

The cutting principle of composite materials basically involves a workpiece-tool-machine system in order to achieve specific surface topography with minimum tool wear and high integrity of prepreg . This is mainly affected by the physical phenomenon of the cutting mechanics such as surface formation, cutting force and heat generation during cutting processes as well as tool geometry and workpiece-machine stiffness.

Koplev et al [11] performed orthogonal machining test parallel and perpendicular to the fibres using a quick-stop device to freeze the cutting process and obtain the chip root. When cutting parallel to the fibres, Koplev et al found the surface to have visible fibres. They also found nearly all fibres were fractured perpendicular to their longitudinal direction. When the composite was machined perpendicular to the fibres, they did not find visible fibres on the surface. Instead, they found the whole surface of the workpiece to be coated with a thin layer of the matrix material. Below the surface layer, a layer of material with cracks was found. In addition, they observed a rather sharp notch with no cracks in front when machining perpendicular to fibre direction. In contrast, a crack was found in front of the notch when machining parallel to fibres. Figure 1.1 shows this effect.

Based on these observations, Koplev et al pointed out that during machining of carbon fibre reinforced plastic (CFRP) perpendicular to the fibres, two separate effects occur near the tool tip. As the tool moves forward, it presses on the composite in front of it causing the composite to fracture and create a chip. At the same time, a downward pressure on the composite below the tool produces fine cracks (about 0.1 to 0.3 mm deep) into the specimen. When the composite is machined parallel to the fibres, the tool applies pressure on the specimen, resulting in chips.

Sakuma [12],[13],[14] conducted a face turning test on glass fibre reinforced plastic (GFRP) cylindrical pipes which contained unidirectional fibres (right-hand winding or left-hand winding). They established a model of cutting mechanisms for glass fibres from their test results shown in Figure 1.2. In cutting the left-hand-wound layer, since the glass fibre tilting in the cutting direction comes to be more tilted by the cutting force with the progress of the cutting edge, it seems that the glass fibres are broken by tension rather than by shearing. On the other hand, in cutting the right hand wound layer, because the glass fibres tilting is opposite to the cutting force with the progress of cutting edge, it seems that the glass fibre are mostly broken by shearing.

Sakuma [15] also conducted a turning (facing) test on CFRP. In this test, the wear patterns and wear land growth rates were analyzed and the cutting speed dependence of tool wear and the relationship between the physical and mechanical properties of tool material and the wear were also analyzed. However, no cutting mechanism of CFRP was given in this test.

Ramulu et al [16] performed turning (cutoff) tests using different grades of poly-crystalline diamond (PCD) inserts. In these tests, they found the same result as those given by Koplev and Sakuma, i.e., each of the four laminates was machined where the fibres were cut parallel or perpendicular to the cutting edge and tilt to or tilt away from the cutting direction. The result obtained by Rumulu proved that the model established by Sakuma in GFRP cutting is suitable for CFRP cutting.

The defect forms of composite due to cutting are fibre debonding, fibre pullout, protruded

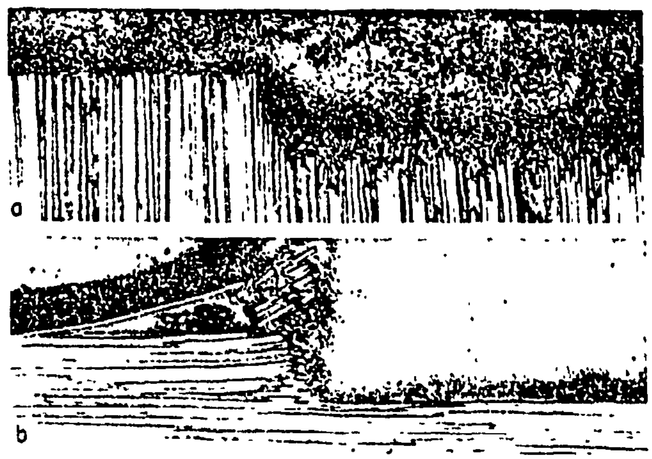

Figure 1.1 Cross section of chips formed (a) from machining in the perpendicular direction and (b) from machining in the parallel direction [11].

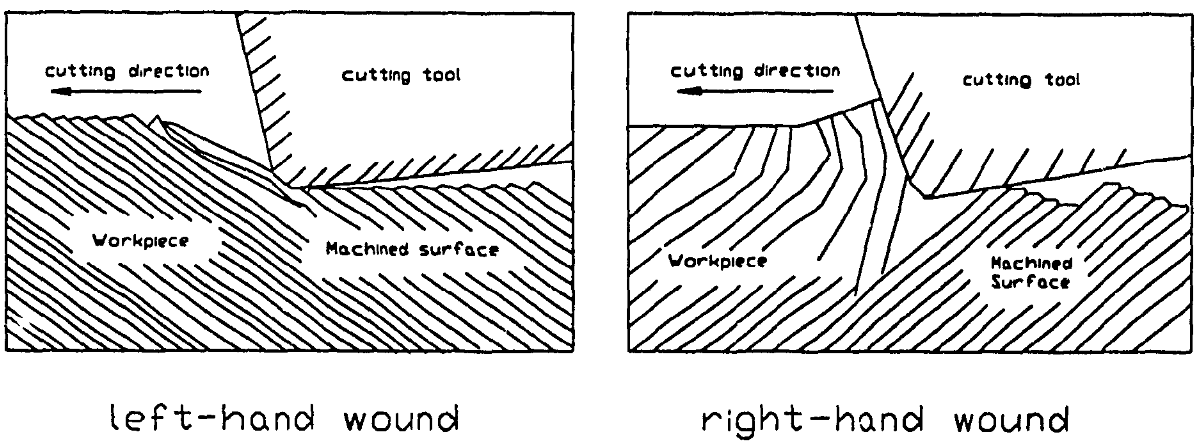

Figure 1.2 The model of cutting mechanisms for glass reinforced composites [14]

uncut fibre, crack and heat-melt.

There are two views on the mechanism of surface formation.

G.SANTHANAKRISHNAN et al [17] reported that in machining of FRP composites, three mechanisms operate. The harder tool wedge enters the softer matrix and removes material by abrasion. The other mechanisms are ploughing and cutting. The chip production process includes crack production parallel to the cutting direction, bending of the fibre and subsequent fractures. During FRP composites machining, a surface layer of the material would be plastically deformed and sheared if it is ductile; brittle material may undergo cracking due to rupture. In general a combination of plastic deformation, shearing and bending rupture alone with cutting of matrix material would take place in FRP composites machining. However, in view of the high flexibility of kevlar fibres in kevlar fibre reinforced plastic (KFRP), the bending rupture is absent and plastic deformation and fibre elongation predominate. In case of GFRP, glass fibre being more brittle and less flexible than Kevlar the failure occurs by all the above means, while in CFRP the carbon fibres being more brittle and the strain at failure being least get crushed and fractured sharply.

Younan [18] in his report pointed out that the cutting mechanism of composites can be a fracture; and that is caused by the wedge action of tool tip. The second stage is the propagation of a crack by tensile stress that results from the bending moment applied to that part of material to be cut. This tensile stress in addition to cause fibre fracture also produces fibre pull out and fibre debonding. In other words, the crack grows from the tool edge beneath the surface of the work material after the tool penetrates and pushes into the material and some plastic deformation occurs, then the chip starts to slide over the rake surface of the tool. The crack grows as a result of the bending moment acting on the chip.

Younan emphasized that the composite cutting mechanism is a crack propagation and not a shear process as in metal cutting.

1.2.1 Factors Affecting the Surface Formation:

Every author mentioned above reported that the fibre orientation has greater influence on the surface formation regardless of fibre type and cutting methods. This is easy to understand because the fibre is the skeleton of composites and the composite behaviour depends on it. When the fibre orientation is changed, the properties of composites will be changed at the same time.

Advanced composites namely GFRP, CFRP and KFRP have different mechanical and thermal properties. It is believed that physical properties of composites have influence on the surface formation. Ductile fracture tends to occur when the deformation rate or strain rate is increased. Temperature has a similar effect, i.e, for a given composite, stress decreases and strain increases with increasing temperature. Composites in general show ductile fracture as temperature rises. Other mechanical properties such as tensile, flexural strength and hardness are also temperature dependent in such a way that they decrease as the temperature rises. Therefore, cutting speed and temperature will affect the cutting process and machinability of composites. SANTHANAKRISHNAN et al [17] performed experiments to explain the mechanism mentioned above. They found that the CFRP machined surface has least fibre pullout and better surface texture with insignificant loose fibres on the surface. During machining the carbon fibre gets crushed and fractures sharply (irrespective of the fibre orientation) because the carbon fibre is brittle and the relatively reduced permissible strain at failure. Figure 1.3 shows typical stress-strain characteristics of different fibres and their composites.

In the case of GFRP at rupture the fibre is less brittle than carbon fibres and also owing to the fibre orientation being parallel or inclined to the cutting direction, the cutting leaves deformed projecting and partially dislocated fibres on the machined surface. The KFRP surface exhibits machined surface with a lot of fussy, delamination, loose, elongated and projecting fibres. Kevlar fibre possesses higher toughness and higher permissible strain at rupture. The inclined fibres fail by elongation resulting in an overall surface with poor surface texture.

Thermal properties of the material have important effects on the cutting process. Properties such as thermal conductivity, thermal expansion coefficient and softening temperature can have considerable effects on machining of composite.

In composite cutting, heat generated is created from two sources. The first source of heat is the conversion of the fracture energy into heat. The heat generated due to fracture energy depends on material toughness, loading rate, depth of cut and radius of tool tip. The second source of heat is from the friction between tool and composites. Friction heat increases with tool surface roughness and tool angle. The heat during composite cutting can have dramatic effects on the tool edge and work material because of low soften temperature and large thermal expansion coefficient. It causes the melt of composites and reduces the tool life due to annealing and softening effects.

Tool geometry also has an effect on the surface formation of composite. The knife should be kept sharp and clean.

Tool material properties (mechanical and thermal) have indirect influence on the surface formation too. Sakuma et al [12]-[15] performed turning test on CFRP and GFRP. They found a phenomenon, i.e., the higher hardness, the smaller the thermal expansion coefficient of the composite, the less tool wear during cutting GFRP and CFRP.

However, they found that the thermal conductivity of tool material has influence on the tool wear during cutting GFRP. The thermal conductivity of tool material almost has no influence on the tool wear during cutting CFRP. Because carbon fibre has large thermal conductivity, the heat generated during cutting can dissipate into the workpiece rather than into tool edge. Thus, prepreg may be cured because of heat during the CFRP cutting.

1.2.2 Factors Affecting the Tool Wear:

In view of the hardness and abrasive reinforcing fibres used in most polymer matrix composites, tool wear in conventional machining is a serious problem with most tool materials. In view of wear mechanism, there are two types, i.e, mechanical wear and thermal crack. Several works about tool wear during composite cutting have been published [12]-[16], [19].

Ranga Komanduri [19] in his paper reported how to select the tool material during composite cutting, KFRP is an inherently tough material, cutting tool should be sharp and clean. Since KFRP is not particularly hard, HSS (high speed steel) or coated (TiN) HSS tools should provide reasonable tool life. Cemented carbide tools on KFRP provide longer tool life and maintain sharper cutting action. These tools could easily handle single - (kevlar-) reinforcing - fibre composites. When hybrid composites containing glass or graphite and kevlar have to be machined, tool wear will be high. Tools with geometrically undefined cutting surface, such as diamond-impregnated and diamond-plated tools, are not recommended for machining KFRP. To avoid fuzz and delamination, backup support is recommended on both entrance and exit sides.

In view of the high hardness and abrasive of glass fibres in GFRP composites, cemented carbide and preferably diamond tools (single-crystal and poly-crystalline) are recommended for machining these materials. If HSS tools can be used to machine GFRPs,

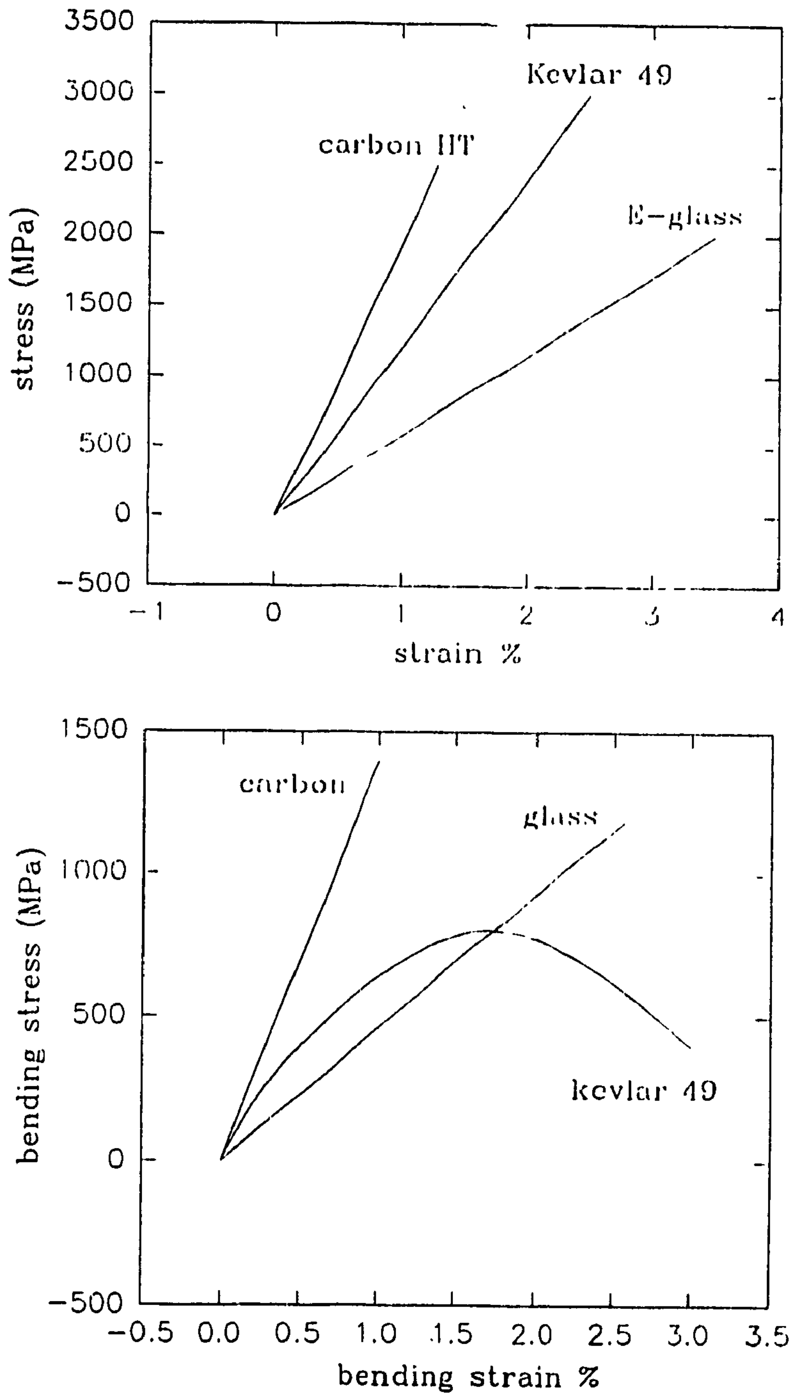

Figure 1.3 typical stress-strain characteristics of different fibres and their composites [20]

they wear rapidly and cutting speed should be kept low enough to avoid overheating the tool. Maintaining the sharpness of the tool is a problem for both HSS and cemented carbide tools due to the glass fibre abrasive action on the cutting tool. The machining of GFRPs can be considered similar to drilling a hole in a resin-bonded grinding wheel except that the abrasive in this case is glass. A dull tool can dissipate considerable heat into the workpiece and can damage the resin-based composites. Although alumina and glass should not be overlooked, Poly-crystalline diamond (PCD) tools are preferred, particularly in the case of GFRP components with a high glass fibre content (about 60 %) which have to be machined to tight tolerance and good surface finish. Rigid machine tools are preferred when machining GFRPs with PCD in order to take advantage of PCD's superior cutting capability.

Hasegawa et al [19] conducted extensive studies on the tool wear when machining GFRPs. They found the tool wear to be predominantly abrasive in nature and proportional to the contact pressure between a glass fibre and tool under a constant cutting length. They divided the tool wear with cutting speed into three regions. At very low speeds they found the tool wear to be negligible and independent of cutting speed and dependent only on the length of cut, with the wear increasing linearly with the length of cut. At intermediate speeds the tool wear was found to increase with cutting speed. At higher speeds tool wear was found to increase rapidly and independently of speed.

SANTHANAKRISHNAN et al [17] used sintered carbides (P20, TiC coated, K20) and

HSS to perform experiments. They found K20 carbides performed better in machining FRP composites.

The higher toughness of the kevlar fibres results in nose deformation and shearing during machining, i.e, the ploughing component of cutting increases. This results in more cutting force during KFRP machining compared to machining other composites. Sinter carbide tools during KFRP machining failed by chip notching without exhibiting any type of normal tool wear. This is due to the fuzzy stranding of the loosened fibres which continuously rub and raise the tool tip temperature. This results in chipping by thermal crack. Sinter carbide tools on machining GFRP exhibit strap wear on flank and secondary side.

Severe wear in the nose region and cobalt matrix pullout leading to the flow of carbide skeleton due to higher cutting temperature is exhibited.

CFRP machining results in predominant crater wear on sintered carbides associated with uniform abrasion marks all along the primary,secondary edges. The carbide particles are abraded due to their affinity to the carbon fibres rather than matrix flow or pull out. Ramulu et al [16] investigate machining of graphite/epoxy composite material using different grades of Poly-crystalline diamond (PCD) inserts. The wear behaviour of the Poly-crystalline diamond (PCD) cutting edge is characterized by small cracks, rounded edges and flank wear. The flank wear growth rate was found to depend on the microstructure of the tool and machining time. The coarser the PCD is, the better the wear resistance. The flank wear was fairly uniform and the wear mechanism was found to be due to mechanical process. The carbide tool exhibited a non-uniform flank wear and dull within 10 seconds of machining time.

Sakuma et al [11],[12] conducted experiments to investigate the effect of the physical properties of tool and cutting temperature on the tool wear. They found that the larger the thermal conductivity and compressive strength, the lower thermal expansion coefficient, the higher the critical speed. (Over the critical speed, the tool wear increases rapidly.) Among these factors, the thermal conductivity is the most important factor and the thermal expansion coefficient and compressive strength are also important . They also investigated the temperature distribution along the tool edge and the relation between temperature distribution and tool material and the relation between temperature distribution and tool wear. In another report, Sakuma et al [13] pointed out the fibre orientation has great influence on the cutting mechanism (fibre fracture mechanism), tool wear and the surface quality of machined surface.

Sakuma [14] also investigated the tool wear in cutting CFRP. They found that cutting speed has a small effect on the wear rate. This phenomenon is different from one in the GFRP cutting. The contact pressure between tool and workpiece has a great influence on tool wear. Hardness and compressive strength is an important factor for reducing the contact pressure. The contact pressure will be reduced with the decrease of thermal expansion coefficient . Thermal conductivity, which is important in cutting GFRP, has little correlation with the wear rate in CFRP cutting. The performance of tool materials is better in the order of K10, CB, M10, P20, CW, TiC, TiN and TaN (carbide and ceramic tool material) in the cutting of CFRP. The performance of ceramic tools which is the lowest in GFRP cutting is relatively high in CFRP cutting.

Very limited studies on the cutting mechanisms of composite (cured and uncured) have been carried out as compared with other conventional materials. Few publications on machining of cured composites are available. Only cutting quality and cutting parameter on uncured composite cutting were mentioned in the literature [3], [5]. Because reciprocating knife can cut a greater number of ply prepreg and the quality of the edges of plies is good visually, it is, therefore, a cost-effective method is also necessary to study the cutting mechanism using this cutting method. This work will be helpful for understanding the cutting mechanism of uncured composite cutting. This fact initiated the present study.

1.3 Review of Metal Cutting

Cutting with a tool can be described as a variety of controlled fractures. Before working on the mechanisms of composite cutting, it is useful to review the mechanisms of metal cutting.

Research in metal cutting has been done for a long time and technology has been developed rapidly in recent years [20] - [30]. The results of this research have been applied to solve practical problems in the machining of metals. Most of the analyses of metal cutting mechanisms are based on the assumption that the metal is an ideal plastic body having a homogeneous structure which yield at the point of maximum shear stress. The structure of composites is totally different from one of metal, which is inhomogeneous and anisotropic. Especially, composite prepreg is composed of hard fibre and soft uncured resin. During the cutting of composite prepreg, the fibre will fracture under the shearing stress and tensile stress. Therefore, traditional analytical method of mechanics of metal cutting can not be applied to solve the problem of metal cutting.

Although there is difference between mechanics of metal cutting and composites cutting, the mechanics of metal cutting is helpful for the understanding of cutting of composite materials. In the research on mechanics of metal cutting , it is the basic chip formation process by which material is removed from the workpiece which is studied. This research is to provide a theory of metal cutting which relates cutting force, tool stresses and temperature, etc., to the cutting condition (cutting speed, size of cut and cutting edge geometry) and work and tool material properties. The problem to be solved can be stated as follows. Given the cutting conditions and the appropriate work and tool material properties, determine the geometry of the chip and of the zones of plastic deformation together with the associated stresses, strain, strain-rate. If the process is essentially one of plastic deformation, the appropriate theory for its solution is plastic theory. For problems of large plastic strain, the most powerful theory available for obtaining solution is plane strain slipline field theory. However, no complete solution to the problem as formulated has been obtained even for the idealized rigid-perfectly plastic work material normally assumed in slipline field theory. Finite element methods can be employed to solve the problem. To date, the usual approach to the problem has been to propose a chip formation model based on experimental observations and then to develop an approximate machining theory from this. The best known model of this kind is the shear plane model of chip formation.

The shear plane model of chip formation shown in Figure 1.4 is based on the experimental observation made by Ernst and others that continuous chip is formed by plastic deformation in a narrow zone that runs from the tool cutting edge to the work-chip free surface. Based on this model, the relation between cutting force and cutting condition can be obtained.

There are two methods, photomicrographs of chip sections and high speed motion pictures, which have been used extensively to observe the different types of material removal process which can take place in metal cutting. In the method of photomicrographs of chip section, a cut is taken under given conditions and stopped as quickly as possible so that the observed deformation is near to that while actually machining of metal.

The problem statement, the approach to the problem and the methods to observe the chip section for metal cutting are good reference to composite cutting. The methods to observe the material deformation during the metal cutting and after metal cutting will be utilized in the cutting of composite prepreg later on.

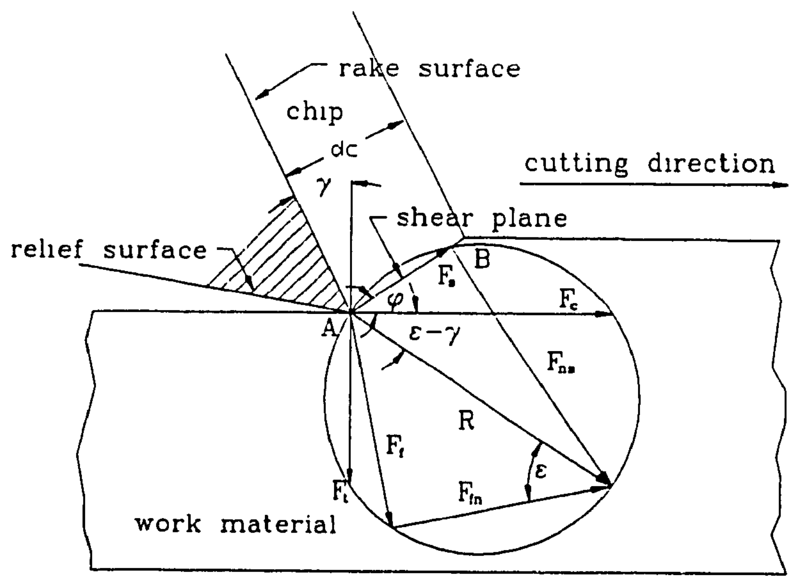

Figure 1.4 Schematic diagram of cutting forces during metal cutting when a shear plane is formed [27].

1.4 Scope of the Present Research

In this thesis, the prepreg embedded with graphite fibres was used to investigate the effect of cutting parameters on cutting quality and evaluate the fibre deformation during and after prepreg cutting. The cutting process considered is of the type in which a piece of prepreg is produced by the fracture of material by the action of the wedge-shape cutting edge. Process such as laser beam cutting (**LBC**), water jet cutting (**WJC**) and electrical discharge cutting (**EDC**) are not considered. The strength of laminate made of cut prepreg under different cutting conditions was also measured to examine the effect of material deformation on the strength of laminate. Scope of the present research is summarized as follows:

1. The effect of cutting parameters of a sign cutting machine on the cutting quality of composite prepreg is examined.
2. The fibre deformation of unidirectional prepreg is studied.
3. The fibre deformation of woven prepreg is studied.
4. The effect of fibre deformation of unidirectional and woven prepreg on the laminate strength is determined.

CHAPTER 2

THE EFFECT OF CUTTING PARAMETERS ON EDGE QUALITY OF PREPREG

2.1 Introduction

Machining of polymeric composites differs from machining of metals. The physical and thermal properties of fibres and polymer matrix are quite different. This together with the orientation of fibres in the matrix affects the machinability of composites. A few papers discuss the peculiarities of machining composites using traditional methods [10] - [19]. No work on machining of composite prepreg has been done.

During cutting of composite prepreg, fibre deflection along cut prepreg often occurs. This, in turn, affects the quality of laminate. In order to make clear how cutting parameters affect the edge quality of prepreg, experiments have been conducted.

2.2 Experimental

2.2.1 Workpiece-tool-machine system

Figure 2.1 shows the experimental setup used in this work involving the tool, workpiece, machine system. Cutting trials have been carried out on composite prepreg, which is

NCT361 - G120, a commercial graphite epoxy prepreg from NEW-PORT Composites Inc.

Prepreg is a kind of composite material in which continuous reinforcing fibre and matrix resins are combined into different unfinished materials that are designed for subsequent use with specific fabrication processes. Using prepreg rather than in-line impregnation of the fibres during the final composite fabrication process can offer significant advantages. Prepreg can have very precisely controlled resin/fibre ratios, highly controlled tack and drape (in the case of thermoset matrices), controlled resin flow during the cure process, and in some case, better control of fibre angle and placement. Prepreg materials can be produced and stored, normally under refrigeration for thermoset matrices, and then used in processes ranging from hand lay-up to highly automated filament winding or tape laying. Processes such as pultrusion and braiding can also use prepreg forms instead of in-line resin impregnation.

The machine tool is CAMM-1 PNC-1800 <SIGN CUTTER> machine supplied by ROLLAND DG CORPORATION. The machine cutting force varies from 30 g to 400 g.

For this machine, cutting speed can be set in 1 cm/s increments within 1 cm/s to 30 cm/s range. The machine tool was connected with a computer through its serial port. A cutting pattern was drawn in the computer using AutoCAD software. This, in turn, is sent to machine tool so that a cutting pattern can be realized.

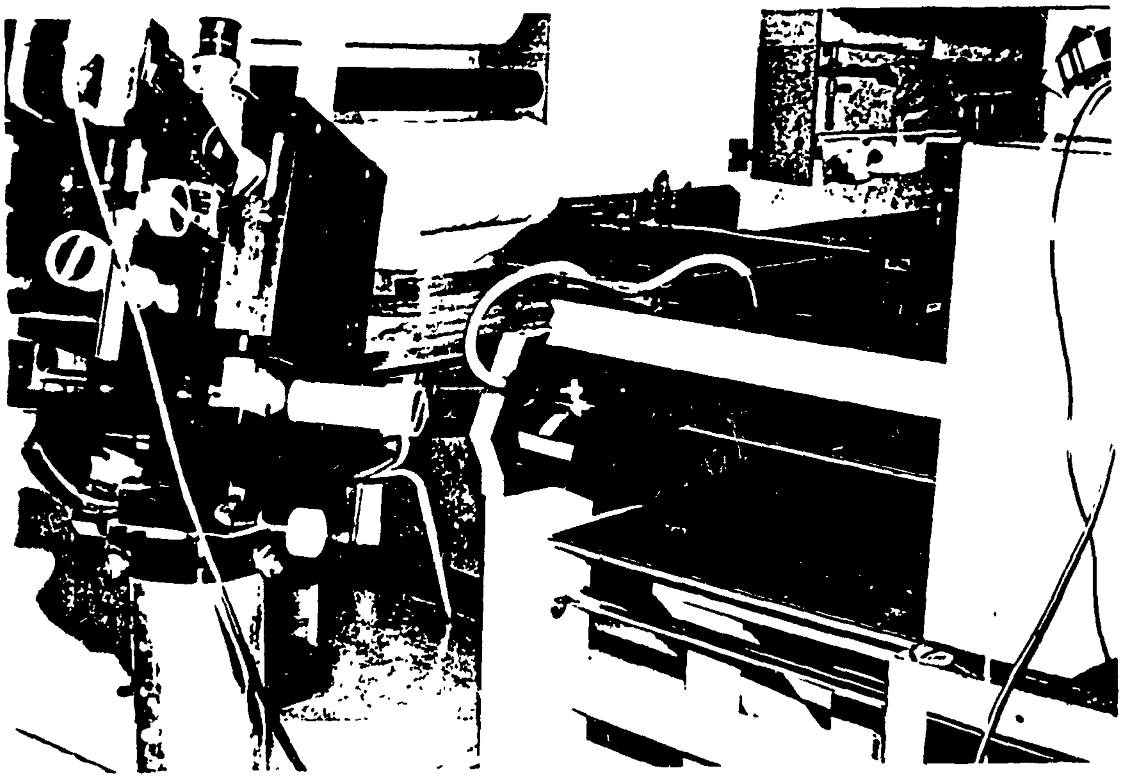

Figure 2.1 Experimental set up for effect of cutting parameters

The cutter is ZEC - U5025, a commercial cemented carbide blade from Roland DG. The knife geometry is shown in Figure 2.2.

2.2.2 Instruments

The cutting process was monitored through a set of equipment which composed of a telescope , video camera, VCR and monitor. The telescope was connected with VCR and monitor. VCR is Panasonic brand (type: PV-A860-K) and monitor is SONY 20" colour TV. Telescope is QUESTAR QM1. The cutting processes can be recorded and replayed. The cut edge of prepreg was observed under the microscope LEITZ ERGOLUX immediately after cutting.

A piece of prepreg 200 mm x 200 mm with paper backing was used for cutting. An additional paper cover was put on the prepreg. Then, the prepreg with backing and cover was put into the sign cutting machine. This is shown in Figure 2.3. The wax impregnated paper, scotch tape of Tartan brand tape "369" 3M, wrighton nylon bagging film and A4000-P plastic were used as cover. Among them, wrighton nylon bagging film and A4000-P plastic was from AIRTECH company. The cutting force was set by slide switch of cutting machine, the cutting speed was set by the computer. The fracture process and material deformation process of prepreg with plastic cover were observed using the equipment mentioned above to study the cutting mechanisms. It was found that the observation of fracture process and deformation process could not be observed clearly. In order to evaluate the material deformation during the cutting and cutting quality, the cut edge of prepreg was observed under the microscope immediately after cutting. Based on the obtained photos. the cutting quality was evaluated.

The objective of the preliminary experiments is to obtain the clean two-cut as shown

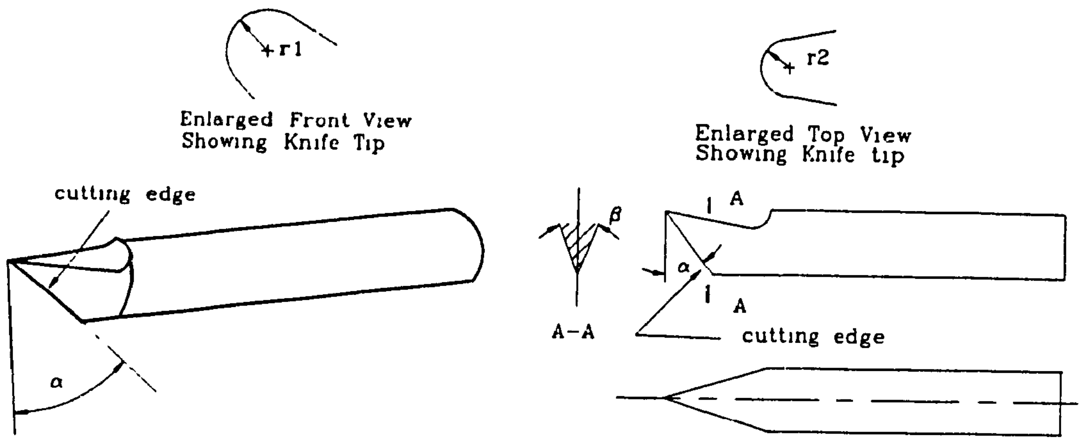

Figure 2.2 Knife for unidirectional prepreg cutting

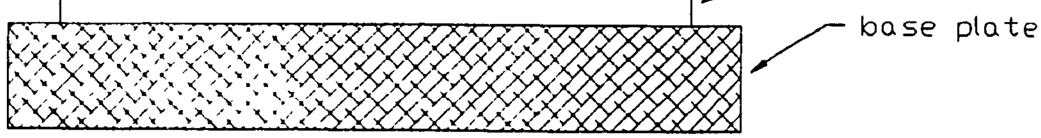

Figure 2.3 Cross section of prepreg with cover during cutting

in Figure 2.4 without squeezing of prepreg for different cases such as unidirectional prepreg (1 ply) and cross-ply and angle-ply (2 plies).

Experiments have been conducted to investigate the effect of knife (geometry and material), cover, cutting force, cutting speed and cutting direction to fibre orientation on the objective, i.e., clean two-cut.

The cutting conditions of the experiment mentioned above are the following:

- Types of cover:
  - wax impregnated paper;
  - The scotch tape of Tartan Brand Tape " 369 " 3M;
  - wrighton nylon bagging films ;
  - A4000 - P plastic.
- Types of knife :
  - cemented carbide blade with α= 45°;
  - cemented carbide blade with α= 60°.

where α is shown in Figure 2.2.

2.2.2 Cutting Parameters

- Cutting directions to fibre orientation as shown in Figure 2.4:

$\delta =$ 0°, 15°, 30°, 45°, 60°, 75°, 90°.

- Cutting speeds: 1 cm/s, 2 cm/s, 3 cm/s, 4 cm/s
- Cutting forces: 180g, 200 g, 250 g, 300 g, 350 g, 400g

- One-cut and two-cut

2.2.4 Quality Evaluation of Cut Prepreg Edge

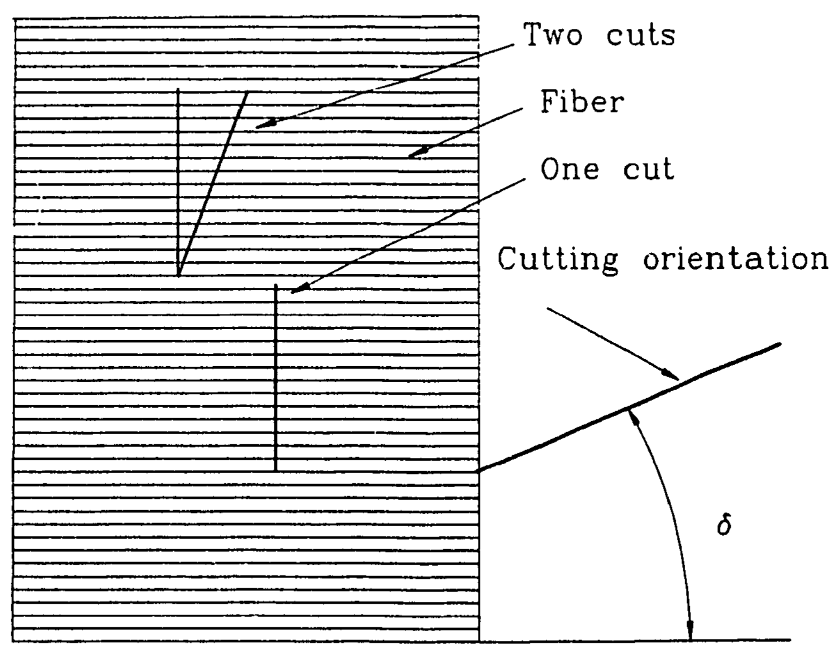

Figure 2.4 Cutting orientation to fibre direction of unidirectional prepreg

A typical photo showing the quality of cut prepreg edge is shown in Figure 2.5. At present, commonly accepted standards of measurement techniques and characteristic indices do not exist. Moreover, the classification of cutting results is often carried out by visual inspection.

Through telescope only obscure wave could be observed on the screen during cutting for the scotchtape cover. For paper cover, plastic cover etc., no wave can be observed. Since the telescope was not suitable for evaluating the edge quality of prepreg quantitatively, two different measured values were used as:

- The ten-point height of roughness R_z, measured by a microscope and calculated from the profiles shown in the photo.
- The peak-to-valley roughness height R_y, measured by a microscope and calculated from the profiles shown in the photo. The R_y is the most sensitive indicator of the degree of damaged zone such as fibre pullout, fibre debonding, uncut fibre.

The definitions of R_z and R_y are shown in Figure 2.6 and described in the following.

Ten point height of Roughness R_z is the average distance between the five highest peaks and the five deepest valleys within the sampling length measured from a line which contacts the deepest point on the profile. Here, the sampling length is the nominal spacing within which the roughness average is determined. From Figure 2.6, R_z is indicated as follow:

$$R_z=[(h_a+h_b+h_c+h_d+h_e)+(h_f+h_g+h_h+h_i+h_j)]/2 \quad (2.1)$$

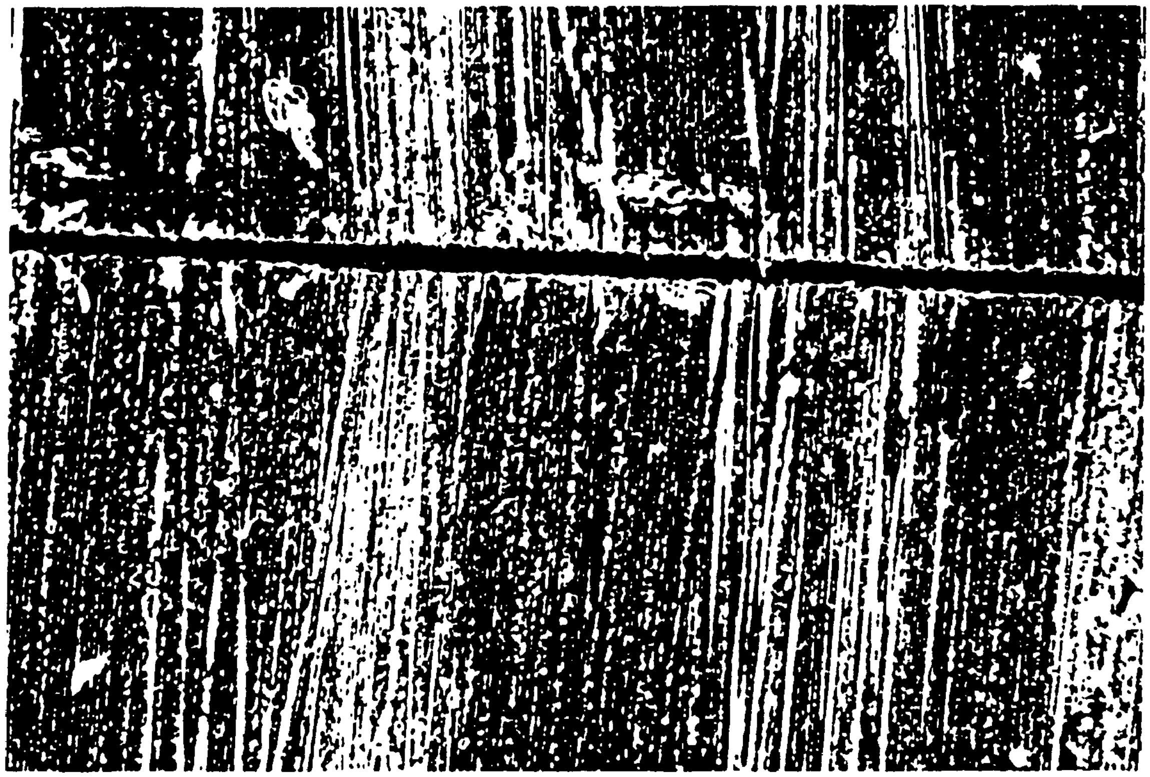

Figure 2.5 The photo showing quality of cut prepreg edge

Maximum peak-to-valley roughness height R_y is the distance between two lines parallel to the mean line that contact the extreme upper and lower points on the profile within the roughness sampling length. R_y is indicated in the Figure 2.6.

$$R_y = h_b \tag{2.2}$$

Through the way defined above, the experimental results are evaluated later on.

2.3 Results and Discussion

One-cut and two-cut experiments with different parameters such as types of cover, knife geometry, knife material, cutting force and cutting speed were conducted to obtain the basic understanding of prepreg cutting.

2.3.1 Cover Effect:

The function of the cover is to constrain the prepreg and prevent it from squeezing as if the prepreg was cured. Whenever cover can not adhere well to the prepreg, squeezing always occurs. The covers used now are wax impregnated paper, scotchtape, wrightlon nylon bagging film and A4000 - P (trade name) plastic.

The scotchtape works well, however, it is hard to take off. Therefore, it should not be used as cover. The A4000 - P (trade name) plastic works well using knife with $\alpha = 45^0$ and does not work well using knife with $\alpha = 60^0$. The wrightlon nylon bagging film and paper works well and it is easy to take off. The film is much more expensive than paper. Therefore, it is recommended that the wax impregnated paper should be utilized as cover in view of economy.

2.3.2 Knife Effect:

2.3.2.1 Functional Requirements of Knife

In view of high hardness and abrasiveness of fibre and preventing the fibre from moving to keep the prepreg integrity, the functional requirement of knife should be wear-resistance and sharpness.

2.3.2.2 Knife Geometry:

Through checking the cut edge, it was found that the squeezing is easier to occur using knife with α=45° than using knife with α=60° during cutting with scotchtape, wrightlon nylon bagging film and paper cover.

Experimental results show that the satisfactory cutting can be obtained using knife with smaller α than 45° and large cutting force.

The prepreg looks like a sheet of paper and is composed of fibre and uncured resin which is soft. The physical situation of prepreg cutting can be described as follows. During prepreg cutting, the knife edge cuts the fibre and the fibre moves forward and bends until it breaks under shear action, compressive and bending action of knife. When the knife cuts the fibre, the subsequent uncut fibre and resin act as elastic foundation. After the fibres break, the knife contacts the resin and ploughs it. Based on this observation, the prepreg cutting can be simplified as that of a concentrated force acting on an infinitely

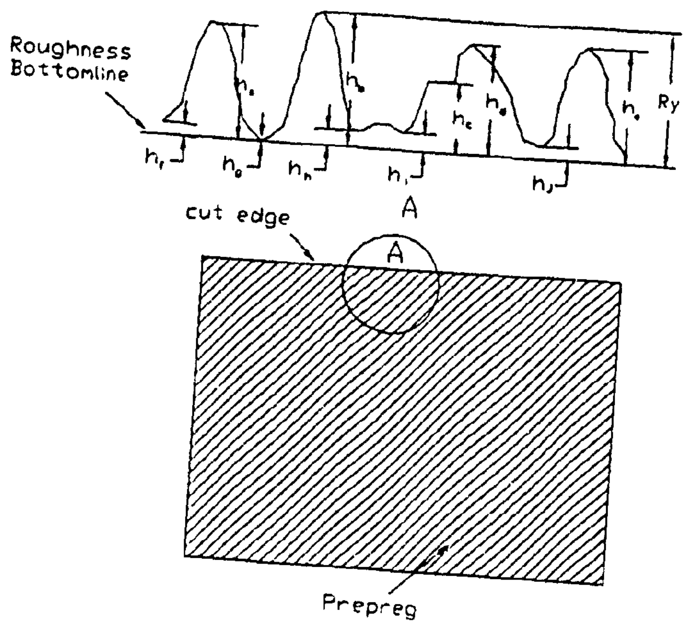

Figure 2.6 Indication for roughness of prepreg cutting

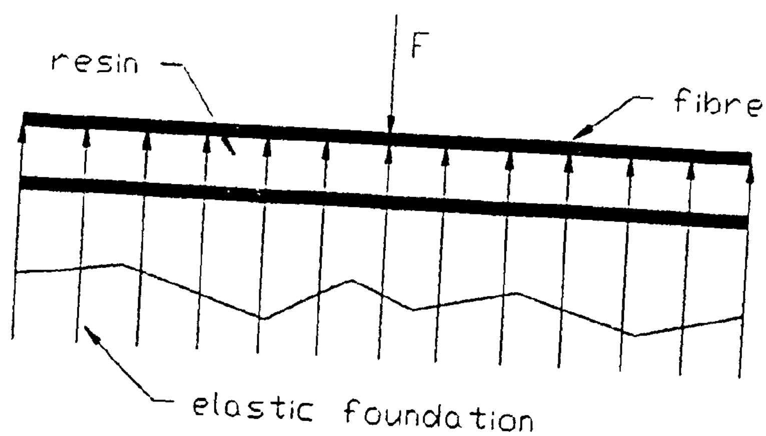

Figure 2.7 Schematic illustration of unidirectional prepreg cutting

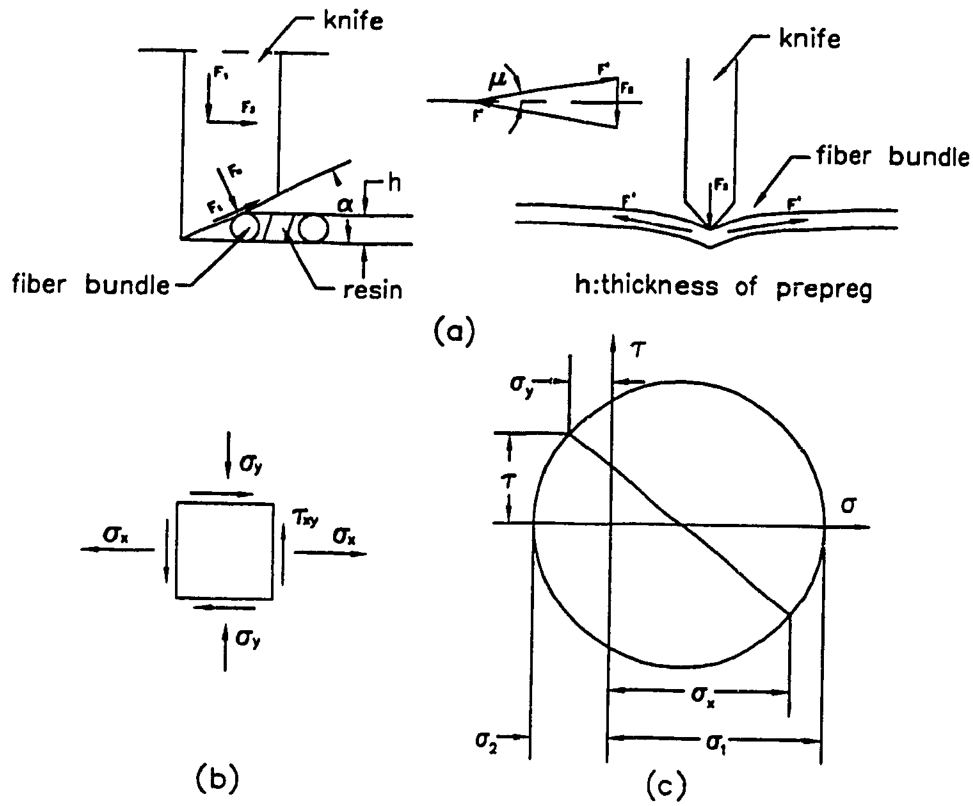

Figure 2.8 The relation between cutting force and primary knife angle α

long beam on an elastic foundation as shown in Figure 2.7. Here, the cut fibre bundle is considered as a beam and the subsequent uncut fibre and resin as foundation. It is reasonable to assume that at points infinitely away from the point of force application, the deflection and the curvature of beam vanishes. This condition can be considered as boundary condition. The situation between cutting force and primary knife angle α is shown schematically in Figure 2.8.

After the description of physical situation of prepreg cutting is completed, the question becomes that how the primary knife angle α affects the cutting performance. The resin of prepreg is soft and the cutting of resin is ploughing. It is assumed that only cutting of fibre has influence on the knife performance. The fibre is brittle material. In the case of brittle materials, which fracture without deformation, a criterion for fracture is furnished by the strength theory developed by Mohr and described as follows[34]:

$$\sigma_1 - \frac{\sigma_{ut}}{\sigma_{uc}} \sigma_2 \leq [\sigma] \tag{2.3}$$

$$[\sigma] = \sigma_{ut} \tag{2.4}$$

Where

σ_{ut} = ultimate strength of the material in tension;

σ_{uc}=ultimate strength of the material in compression;

σ_1 =maximum principle stress;

σ_2 =minimum principle stress.

The tensile strength of graphite fibre is 1.2 GPa [37]. The compressive strength of graphite fibre is about 0.9% of Young's modulus [38] so that it is 1.557 GPa. Therefore, σ_{ut}/σ_{uc} is equal to 0.77.

It is difficult to observe what is really happen at the contact point between knife and fiber bundle. Therefore, the following derivation for the effect of knife angle α on the ultimate stress is only an estimate. As far as this question is concerned, the stress state of fiber under the action of knife is also shown in Figure 2.8. Based on Figure 2.8,

$$F' = \frac{F_2}{2\sin\mu} \tag{2.5}$$

$$V = F_2 \tag{2.6}$$

Where

F' = force along the fiber;

V = shear force in the cross section of fiber.

$$\sigma_x = \frac{F'}{A} = \frac{F_2}{2\pi R^2 \sin\mu} \tag{2.7}$$

$$\sigma_y = \frac{F_1}{l(\alpha)} = \frac{F_1 \sin\alpha}{h} \tag{2.8}$$

$$\tau = \frac{4}{3}\frac{V}{A} = \frac{4}{3}\frac{r_2}{\pi R^2} \tag{2.9}$$

Where

σ_x = tensile stress along the fiber;

σ_y = compressive stress perpendicular to fiber;

τ = shear stress along the cross section of fiber;

A = area of cross section of fiber;

R = radius of fiber bundles;

l = contacting length bewteen knife and fiber;

h = prepreg thickness;

Based on the stress state shown in Figure 2.8 (b), a Mohr's stress circle shown in Figure 2.8 (c) was drawn in order to decide the principle stress σ_1 and σ_2. From it, σ_1 and σ_2 are

$$\sigma_1=\frac{\sigma_x-\sigma_y}{2}+\sqrt{\tau_{xy}^2+(\frac{\sigma_x+\sigma_y}{2})^2} \tag{2.10}$$

$$\sigma_1=\frac{\sigma_x-\sigma_y}{2}-\sqrt{\tau_{xy}^2+(\frac{\sigma_x+\sigma_y}{2})^2} \tag{2.11}$$

Substitute σ_1 , σ_2 into equation (2.3), then,

$$\sigma_m=(1-\frac{\sigma_{ut}}{\sigma_{uc}})\frac{\sigma_x-\sigma_y}{2}+(1+\frac{\sigma_{ut}}{\sigma_{uc}})\sqrt{\tau_{xy}^2+(\frac{\sigma_x+\sigma_y}{2})^2} \tag{2.12}$$

From equations 2.7,2.8.2.9 and 2.12, it is found that only σ_y is the function of knife angle α. In order to decide how the primary knife angle α affects knife performance, let σ_x ,τ, F_1/h equal to unity, then,

$$\sigma_m=0.115(1-\sin\alpha)+1.77\sqrt{1+(\frac{1+\sin\alpha}{2})^2} \tag{2.13}$$

From equation 2.13, different σ_m corresponding with different values of primary knife

α	10°	20°	30°	40°	45°	50°	60°	70°	80°
σ_r	2.094	2.147	2.207	2.27	2.368	2.388	2.436	2.473	2.495

Table 2.1 Ultimate stress value for different values of α

angle α can be found and shown in table 2.1. From table 2.1, it is found that the larger the primary knife angle α, the better is the knife performance. This verifies the previous result, i.e, the performance of knife with $\alpha = 60°$ is better than with 45°. When two-cut was conducted by hand, it was found that the satisfactory cutting can be obtained using knife with α smaller than 45° and large cutting force. If α is too large, bending will play a major role and cause large fibre movement, even squeezing of prepreg. Therefore, when "one cut" is conducted, the knife with α=60° has better performance than α=45° because squeezing seldom occurs for "one cut" case. When two-cut is conducted, the knife with α=45° is a better choice so that squeezing can be avoided. However, enough cutting force is required to promote shear and compressive action to make the fibre fracture.

The other consideration for knife geometry is knife radius. The graphite fibre is brittle and the strain at failure is small, the fibre gets crushed and fractured sharply. Small radius of knife can reduce the contact area between knife and prepreg so that the indentation stress will be increased. Thus, the graphite prepreg can be cut easily. As shown in Figure 2.2, small β is helpful for reducing the small radius r_1.

The configuration of knife geometry shown in Figure 2.9 can be taken into consideration to find the optimum knife geometry. In Figure 2.9, the configuration (a) is normal case. Configuration (b) can make the radius r_1 small and cut prepreg easily as mentioned above. The shortcoming of configuration (b) is that the strength of knife edge is low and it will cause the break of cutting edge. In configuration (c), the knife will become strong and last longer. Meantime, the knife can be ground more times than one of configuration (b) so that it is more economical than one in configuration (b). The slot of configuration (d) is to contain the chip and then reduce the heat so as to improve the life of cutting edge. In prepreg cutting, because the thickness of prepreg is small, the contact area between fibre and knife is very small and there is no chip. Therefore, configuration (d) is not suitable at this point.

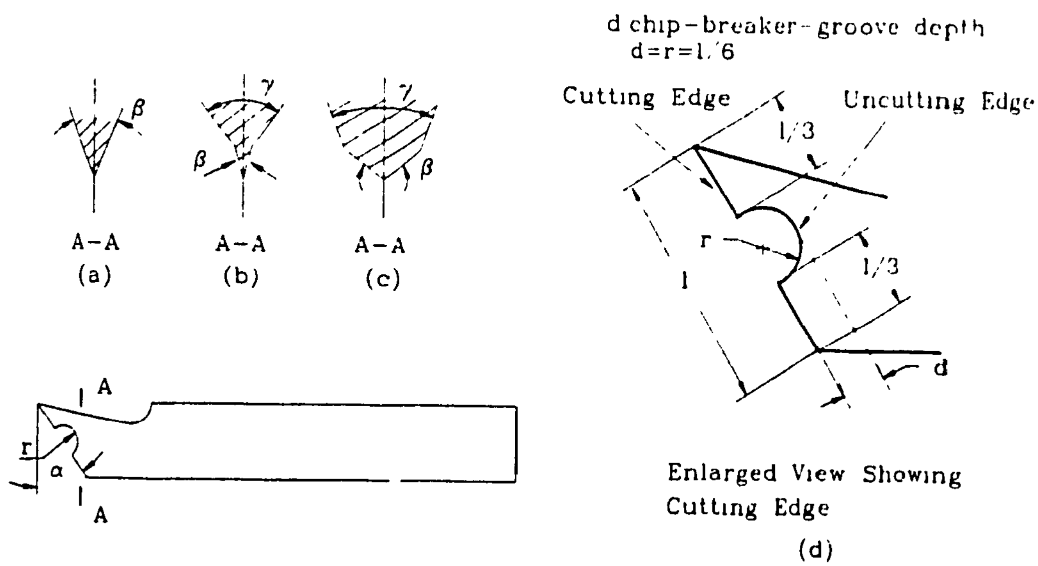

Figure 2.9 Schematic illustration of knife geometry configuration

2.3.2.3. Knife Material

In general, there are three important considerations for knife material which are high-temperature stability (HTS), abrasive wear resistance (AWR) and resistance to brittle fracture (RBF). As a material is made more refractory (high HTS), it becomes easier to wear (low AWR), it also becomes more brittle (low RBF).

In view of the high hardness and abrasiveness of graphite fibres in graphite fibre reinforced prepreg, the HSS knife is not suitable for cutting the graphite fibre reinforced prepreg because of its low AWR. Under the projection instrument , the tip of knife composed of M2 steel used in these experiments is dull and there is no radius r_1 , r_2 and no thermal crack as shown in Figure 2.2 . There is a crater on the edge of the knife. It is believed that the wear mechanisms of knife during graphite prepreg cutting is mechanical wear. The carbide particles are abraded due to their affinity to carbon fibres. In order to maintain the sharpness of knife, the selection of proper knife material is important. M. Ramulu et.al [16] conducted some investigation on machining of cured graphite/epoxy composite using different grades of poly-crystalline diamond inserts. They found that the surface quality of machined graphite/epoxy remains the same, or even gets better as the cutting time is increased, regardless of the Poly-crystalline diamond (PCD) grade. However, the carbide cutting tool exhibited a non-uniform flank wear and was dull within 10 seconds of machined time. Another author, Ranga Komanduri [19] also pointed out that maintaining the sharpness of the tool is a problem for both HSS and cemented carbide tools due to the glass fibre abrasive action on the cutting tool. Poly-crystalline diamond (PCD) tools are preferred, particularly in the case of GFRP with a high glass content . Moreover, the contact pressure between tool and workpiece has a great influence on tool wear. As mentioned before, the satisfactory cutting of two-cut can be obtained using knife with α smaller than 45° and enough cutting force, the compressive strength of knife material is an important factor for reducing the contacting pressure. Therefore, it is strongly suggested that the coated carbide, cermet carbide and poly-crystalline diamond should be utilized as knife material because of their high abrasive wear resistance.

2.3.3 Effect of Cutting Orientation to Fibre Direction:

The edge quality is significantly influenced by the fibre orientation in the graphite/epoxy prepreg . Define the angle between fibre orientation and cutting direction as δ as shown in Figure 2.4. Meantime, define the edge where the fibre tilts against the cutting direction as edge A and the edge where the fibre tilts in the cutting direction as edge B as shown in Figure 2.10. The morphology of cut edge of the graphite/epoxy prepreg was observed under microscope LEITZ ERGOLUX with camera immediately after cutting. The photo of morphology of cut edge was taken at the same time. The results are summarized in table 2.2.

In terms of analysis above, the fibre orientation to cutting direction has great effect on the cut edge quality. The cut edge quality can be divided into three domains. The first domain is 0°. The second one is from 0° to 45° and the third is from 45° to 90°. The worst edge quality is the 15° case. The quality above 45° is acceptable. The edge quality increases as the angle δ increases from 0° to 90°. The best case is " $\delta = 0°$ " and " $\delta=90°$ " .

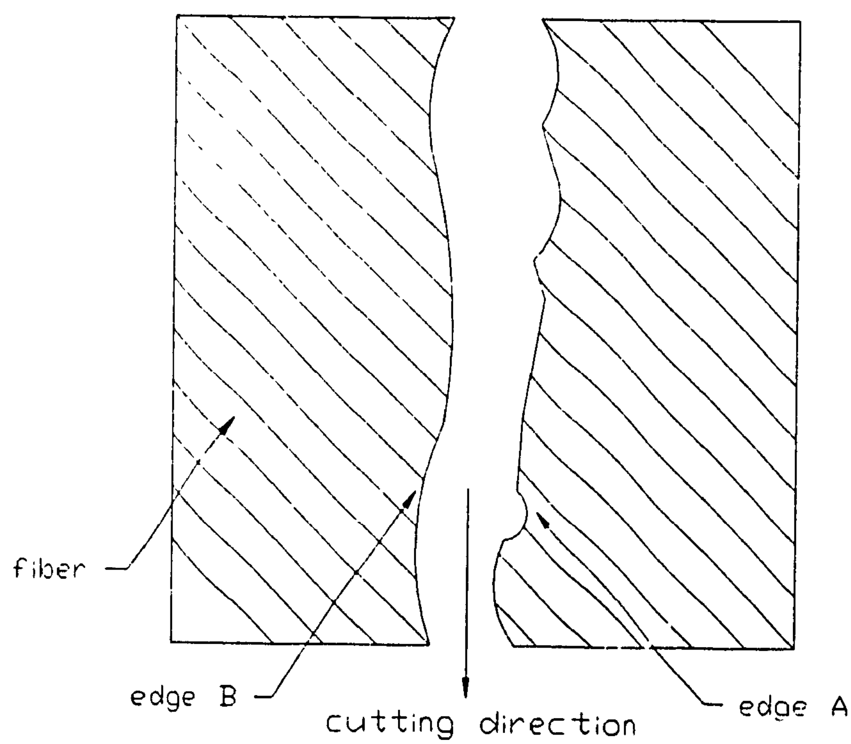

Figure 2.10 Effect of fibre orientation on edge quality for unidirectional prepreg

δ	Observations
0°	It is easiest case for cutting. The knife does not cut the fibre and only cut the resin. The edge quality is very good.
15°	The photo of case " δ = 15° " is shown in Figure 2.11. The edge A is ragged. In the edge A, the broken fibre and separation between fibres can be found. The edge A is " saw tooth" edge and much more ragged than the edge B. In this situation, the material removal mechanisms include a combination of shearing, micro-bending and compressive crack. R_z= 4.2; R_y=10.
30°	The photo of case " δ = 30° " is shown in Figure 2.12. The edge B is smooth. The edge A is ragged. Separation between fibres appears. In some area, the fibre cleavage inside the prepreg away from the edge can be found. For the edge B, the material removal mechanisms is bent through tension. For the edge A, the material removal mechanisms is shearing and compressive crack . That is why some separation between fibres appears in the edge A. The " δ = 30° " case is similar to the " δ = 15° " case. R_z = 1.3; R_y = 3.

Table 2.2 Observations of effect of cutting orientation to fibre direction

δ	Observations
45°	The photo of case " $\delta = 45°$ " is shown in Figure 2.13. The edge B is smooth. The cut edge A is little ragged. No separation between fibres and " cleavage " appear. $R_z = 1.2$; $R_y = 3$.
60°	The edge B is smooth. The edge A is little ragged. The situation is similar to the case "$\delta = 45°$ ". $R_z = 1.06$; $R_y = 2$.
75°	The photo of case " $\delta = 75°$ " is shown in Figure 2.14. The edge B is smooth. The edge A is little ragged. No separation between fibres and "cleavage" appears. Bending fracture is a dominant material removal mechanism. There are fibre movement and intact fibre fracture surface. $R_z=1.2$; $R_y = 2$.
90°	The sides of edge are the same and smooth. No separation between fibres and " cleavage" can be observed. Bending fracture is dominant material removal mechanism. $R_z = 0.6$; $R_y = 2$.

Table 2.2 Observations of effect of cutting orientation to fibre direction (continued)

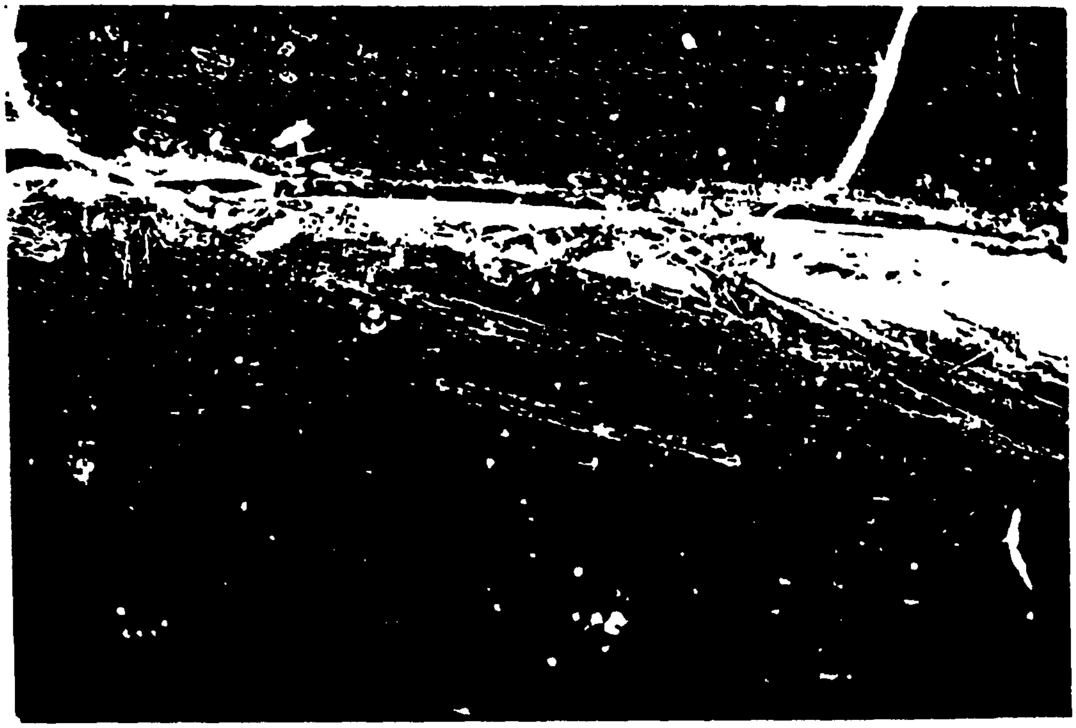

Figure 2.11 Cutting result for the case " $\delta = 15°$ " of unidirectional prepreg cutting

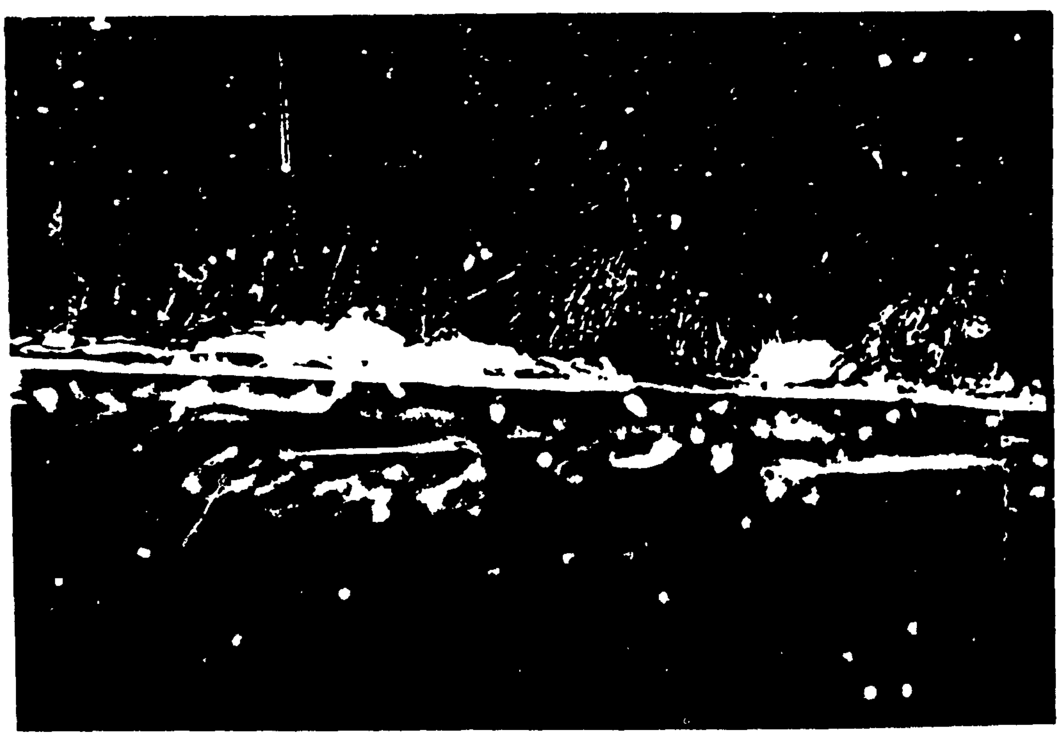

Figure 2.12 Cutting result for the case " $\delta = 30°$ " of unidirectional prepreg cutting

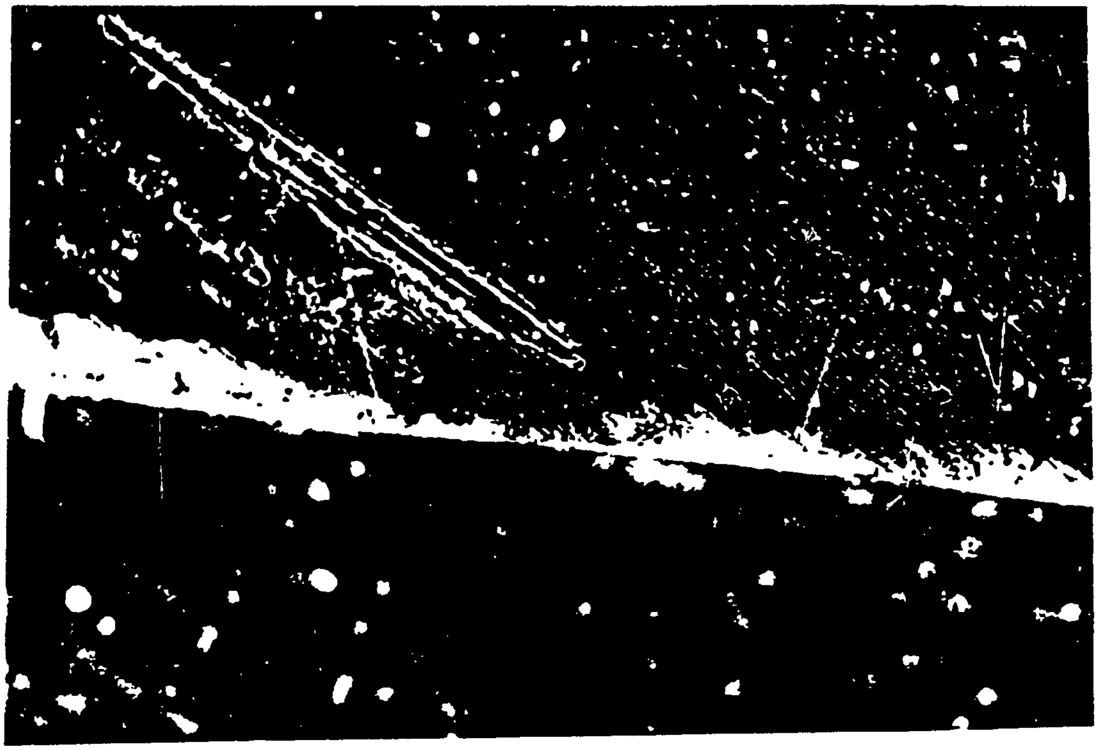

Figure 2.13 Cutting result for the case " $\delta = 45°$ " of unidirectional prepreg cutting

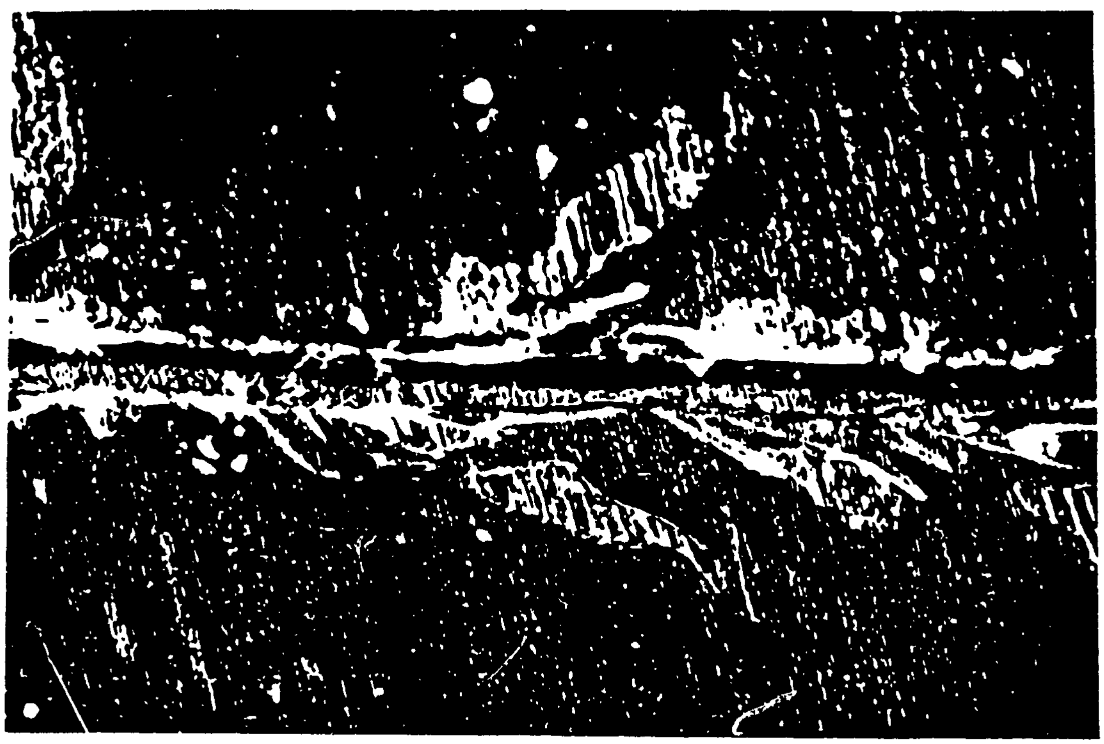

Figure 2.14 Cutting result for the case " $\delta = 75°$ " of unidirectional prepreg cutting

2.3.4 Cutting Speed Effect:

The experiments on cutting speed effect were conducted under the following conditions :

cutting speed:	1cm/s to 4 cm/s;
cutting force:	400 g;
cover:	scotchtape;
knife:	cemented carbide knife $\alpha = 45^{o}$;
fibre orientation to cutting direction:	90^{o}.

The photo of morphology of cut prepreg edge was taken using the camera connected with microscope LEITZ ERGOLUX. From the photo, the cut edge looks smooth and no separation between fibres and no " cleavage " can be observed for the different cutting speeds with the condition mentioned above. To some extent, the cutting speed also has some effect on the edge quality. The cut edge is smoother for 4 cm/s cutting speed as compared to 1 cm/s. This is shown in Figures. 2.15 and 2.16. In summary, the observations are shown in table 2.3.

2.3.5 Cutting Force Effect:

As mentioned in section on knife geometry, the cutting force has effect on the quality of the cut. Experiments were performed to investigate it and the experimental condition were:

fibre orientation to cutting direction: 90°;

cutting speed: 1 cm/s;

cover: scotchtape;

knife: cemented carbide knife with α= 60°.

The experimental observations are shown in table 2.4.

cutting speed	observations
1 cm/s	the cut edge looks smooth and no separation between fibres and no "cleavage" can be observed. R_z=1.6, R_y=2.5;
4 cm/s	the cut edge looks smooth and no separation between fibres and no "cleavage" can be observed. R_z=1.1, R_y=2.

Table 2.3 Observations of cutting speed effect

cutting force	Observations
180 g	some uncut fibres.
200 g	some uncut resin; two sides of cut edge look smooth; no separation between fibres and no " cleavage " can be observed. R_z=0.96; R_y=2.
250 g	the situation is almost same as one of "200 g" case; R_z=0.9; R_y=1.5.
300 g	squeezing occurs.
350 g	squeezing occurs.
400 g	the situation is similar to "200 g" case and "250 g" case; R_z=1; R_y=2.

Table 2.4 Observations of cutting force effect

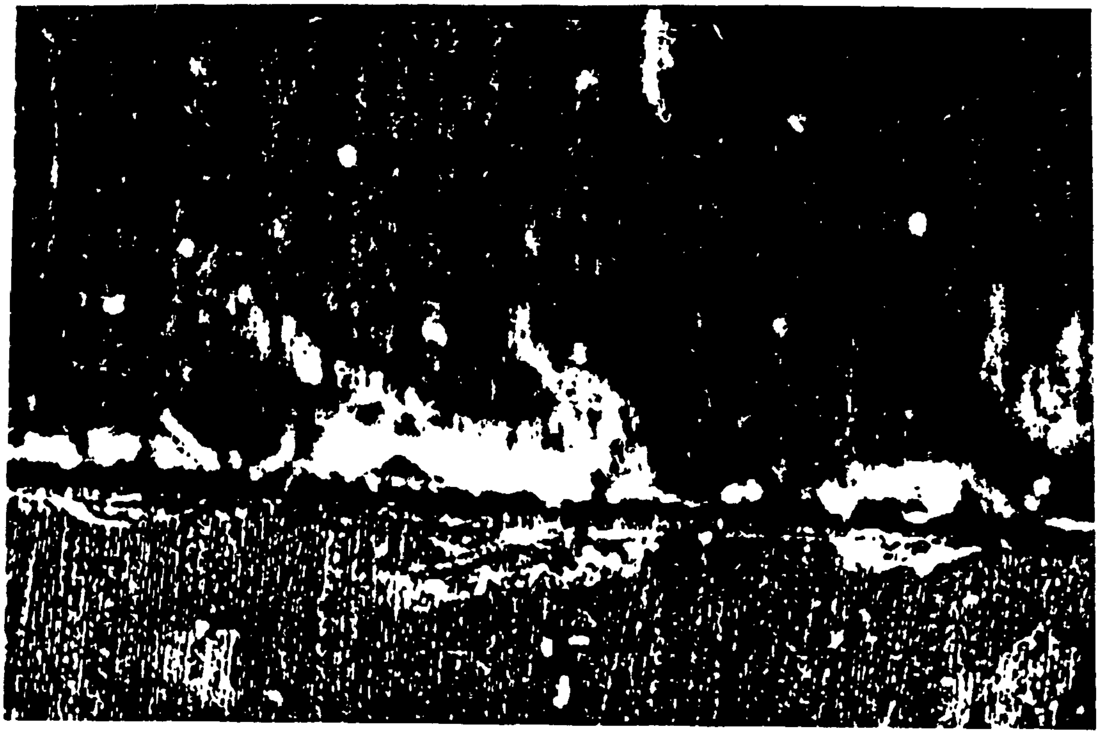

Figure 2.15 Cutting result using cutting speed 1 cm/s for unidirectional prepreg cutting

Figure 2.16 Cutting result using cutting speed 4 cm/s for unidirectional prepreg cutting

2.3.6 Conclusions

Based on the information presented above, the following conclusions are drawn.

1. Cover is the most important factor among the parameters. Without the cover, the squeezing can not be avoided. Wax impregnated paper is the best candidate for cover.
2. In order to avoid squeezing, small primary knife angle α should be chosen to promote shearing action rather than bending fracture. Small radius of knife is required.
3. Coated carbide, cermet carbide and poly-crystalline diamond should be utilized as knife material.
4. For cutting orientation to fibre direction δ, the best quality is the case of " δ= 0° and 90° ". The second one is the case of " δ = 45° to 90° ". The worst is "the range of δ = 0° to 45° ".
5. The cutting speed has no significant influence on the cutting quality.
6. In order to cut prepreg well, enough cutting force is required.

2.3.7 The Successful Realization for Clean Two-Cut with $\psi = 5°$

Based on the observations and conclusions on one-cut, the investigation on clean two-cut was performed using the following conditions:

primary knife angle α: 60°;   cover: wrightlon nylon bagging films;

cutting force: 400 g;   cutting speed: 1 cm/s.

It is found that under the above conditions if ψ is larger than 45°, it is easy to obtain good quality, i.e., clean two-cut. If ψ is smaller than 45°, it is easy to cause squeezing of prepreg.

It is also found that the order of each cut is very important for cutting quality. Figure 2.17 shows the different cut pattern of two-cut.

Each of the patterns was investigated to find a suitable pattern under which the clean two-cut can be obtained for small ψ using the following conditions:

knife angle α: 45°;   cover: wax impregnated paper;

cutting force: 400 g;   cutting speed: 1 cm/s.

The reason to chose knife with α= 45° rather than 60° is to promote shear action rather than bending fracture in order to avoid the large fibre deflection based on the conclusion 2 in section **2.3.6**.

Finally, using the new knife with α= 45°, wax impregnated paper cover, 400 g cutting force, 1cm/s cutting speed, the clean two-cut with $\psi = 5°$ can be obtained through the sign cutting machine. Figure 2.18 shows the photo of this result.

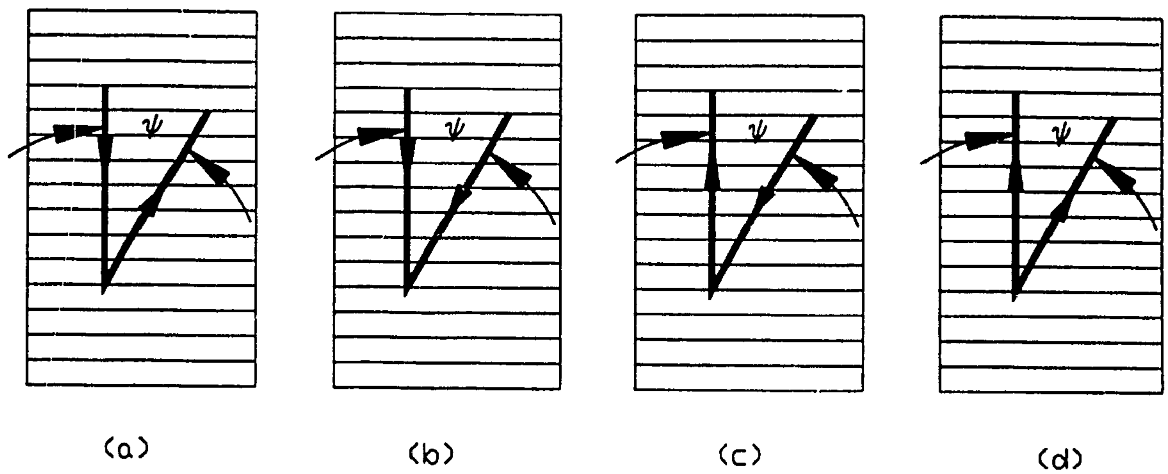

Figure 2.17 The cut pattern of two-cut

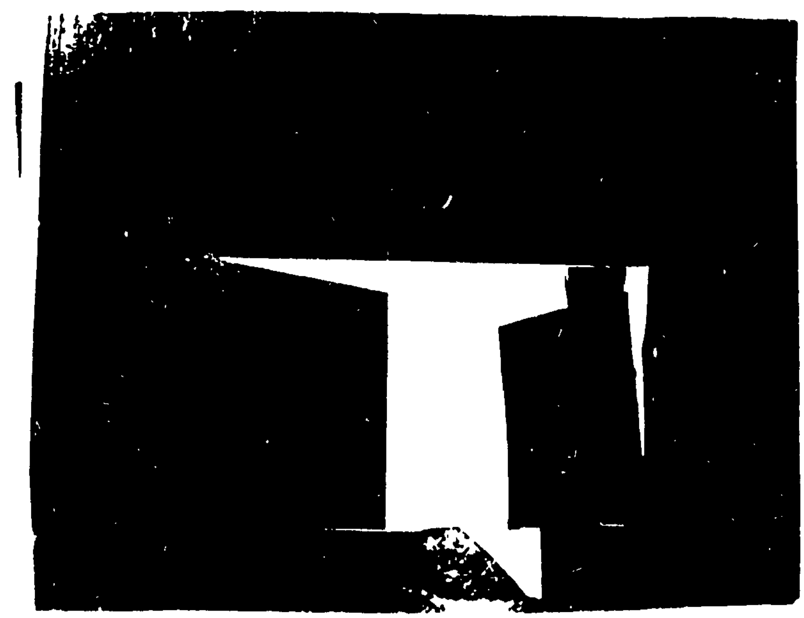

Figure 2.18 Result of clean two-cut with $\psi = 5^{\circ}$

CHAPTER 3

PREPREG FIBRE DEFLECTION DUE TO CUTTING AND ITS EFFECT ON STRENGTH OF LAMINATES

3.1 Introduction

Due to the superior strength-to-weight and stiffness-to-weight ratio, composite materials are used increasingly in high performance applications. Although composite parts are usually produced by moulding and filament winding process etc., many high precision parts must be cut in order to meet tolerance requirements. While much work has been done in studies on mechanical behaviour and mechanics of materials, little has been done in the area of cutting. Because the reliability and precision of composites are critical, a better understanding of the behaviour of such materials is required. Delamination is one of the most important defects in composite. When using knife to cut the composite prepreg, the fibre deflection may occur and cause the delamination of laminates made from the cut prepreg with fibre deflection along the cut edge of prepreg. In order to make clear this problem, experiments have been done to investigate the fibre deflection of prepreg due to cutting and the effect of fibre deflection along the cut edge of prepreg on the delamination and strength of laminates.

3.2 Unidirectional Prepreg Fibre Deflection due to Cutting

3.2.1 Experimental

A composite prepreg was chosen in this study: unidirectional prepreg (NCT-301, a commercial graphite epoxy unidirectional prepreg from NewPort Composite Inc.). The cutting knife used in this experiment is made from steel [Brand name: MASTERCRAFT Utility knife]. The knife was operated by hand. In the experiment, both sharp knife and dull knife were used. Here, the sharp knife means the new knife whose edge width is 5 μm. In order to obtain the dull knife quantitatively, the prepreg used in the experiment was cut for 20 meters long using a new knife. After that, the width of the knife edge became 75 μm. They were evaluated quantitatively by optical microscope and shown in Figure 3.1.

The experimental set up used in this investigation is shown in Figure 3.2. Two types of backing plate (aluminium plate and steel plate) were used to investigate the effect of stiffness of backing plate on the fibre deflection . The prepreg was secured on the plate by scotchtape. The prepreg size on the plate was 300 mm x 180 mm. The measuring system composed of light source, telescope, video camera,VCR and monitor. The light source was intralux 6000. QUESTAR QMI was used as the telescope. The video camera was JVC product . VCR was made by Panasonic, PV-A860-K. The monitor was SONY 20" colour TV.

The fibre deflection was magnified by telescope and image was shown on the screen of monitor through camera adapter. Finally, the fibre deflection can be measured on the screen of monitor. The magnification for measuring the unidirectional prepreg is 150. An optical microscope was used to verify the results later on.

3.2.2 Fibre Deflection in the Contacting Area between Knife and Unidirectional Prepreg

Schematic of fibre deflection in the contacting area between knife and unidirectional prepreg is shown in Figure 3.3 and was observed on TV screen which is connected to telescope QUESTAR QM1. Figure 3.4 shows the photo of fibre deflection in the contacting area between knife and unidirectional prepreg under the condition (sharp knife with $\alpha = 60^o$, aluminium backing plate). The sharp knife and dull knife with $\alpha = 30^o$ and 60^o were used to investigate their effect on the fibre deflection. The formulas were set up to express the curvature of fibre in the contacting area as shown in Figure 3.3 using bold lines . In order to create these equations, a coordinate system was established. The original point of this coordinate system is located in the bending point of fibre. The X-axis has same direction as cutting direction. Under this coordinate system, three points on the deflected fibre were measured. The coordinate of these points are put into equation $Y = aX^2 + bX + c$ and the coefficients of curvature equations can be determined. A computer code was programmed to determine the coefficients of the curvature equations. Figures 3.5 to 3.8 show the fibre deflection during the contacting area and its curvature formula for the following cases:

- dull knife, primary knife angle $\alpha = 30°$, aluminium plate backing;
- dull knife, primary knife angle $\alpha = 60°$, aluminium plate backing;
- sharp knife, primary knife angle $\alpha = 30°$, aluminium plate backing;
- sharp knife, primary knife angle $\alpha = 60°$, aluminium plate backing.

3.2.3 Fibre Deflection after Cutting of Unidirectional Prepreg

The patterns of fibre deflection after cutting were investigated using QUESTAR QM1 and were observed on TV screen. Moreover, the time dependent behaviour of fibre deflection after cutting was observed. Figure 3.9 is the photo showing the fibre deflection after cutting for unidirectional prepreg under the conditions (sharp knife with $\alpha = 30°$, aluminium backing plate). Figures 3.10 to 3.13 show typical fibre deflection after cutting for the following cases under the condition of sharp knife with $\alpha = 30°$:

- δ=90° cutting with aluminium plate;
- δ=90° cutting with steel plate;
- δ=45° cutting with aluminium plate;
- δ=45° cutting with steel plate.

It is observed that under the action of cutting force, fibres were bent. This result is verified by optical microscope. In the figure, the initial fibre orientation is given.

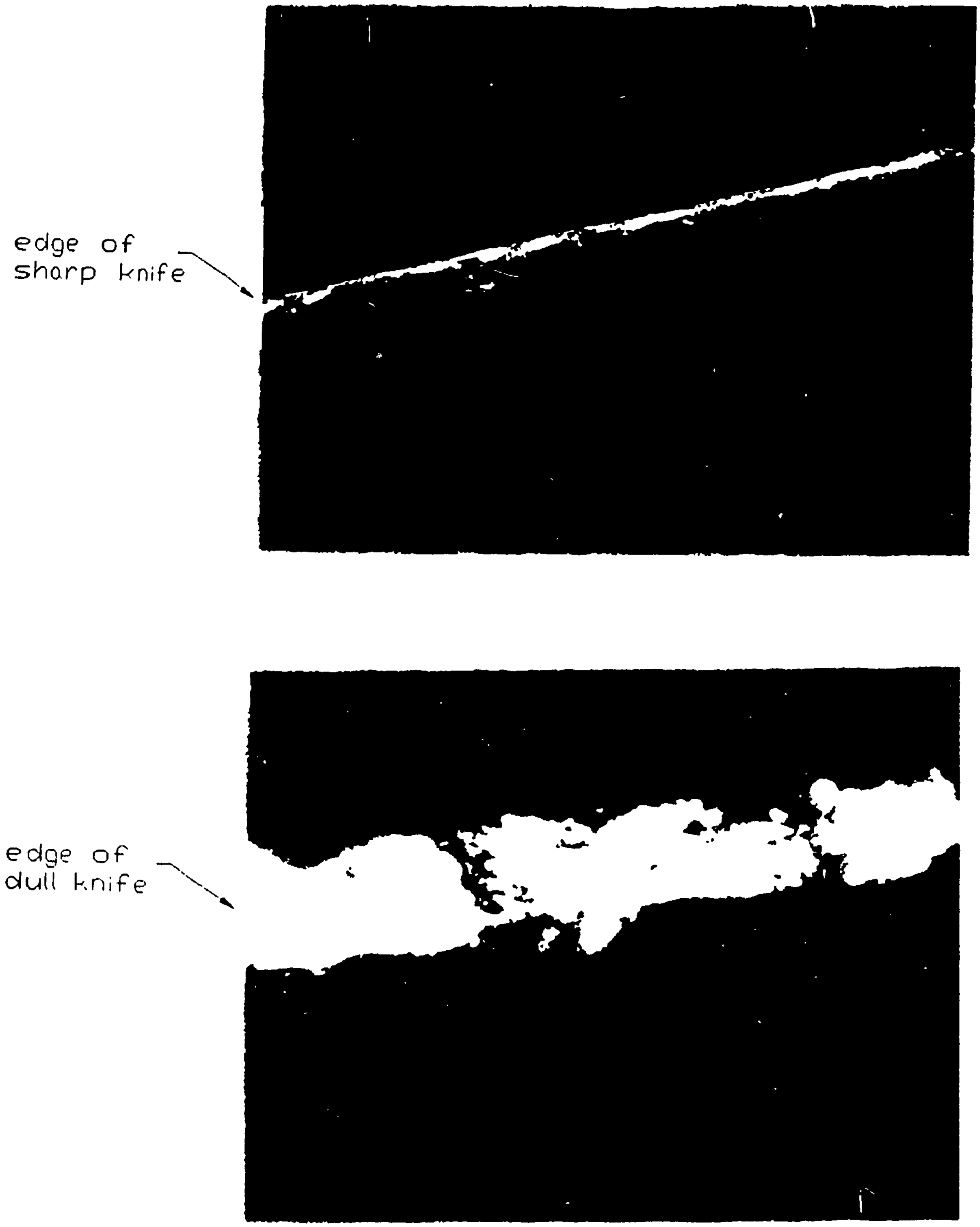

Figure 3.1 Photo of knife edge under the microscope for sharp and dull knife Magnification: 400.

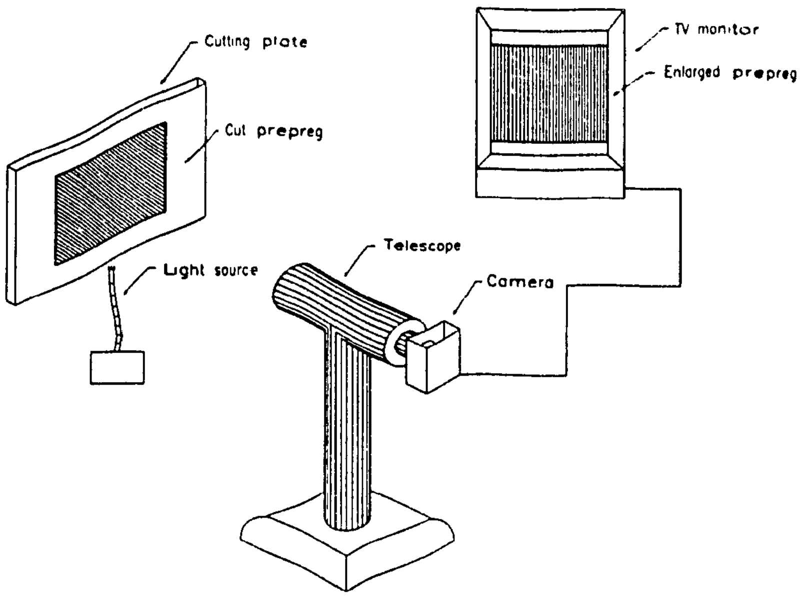

Figure 3.2 Experimental set up for fibre deflection measuring

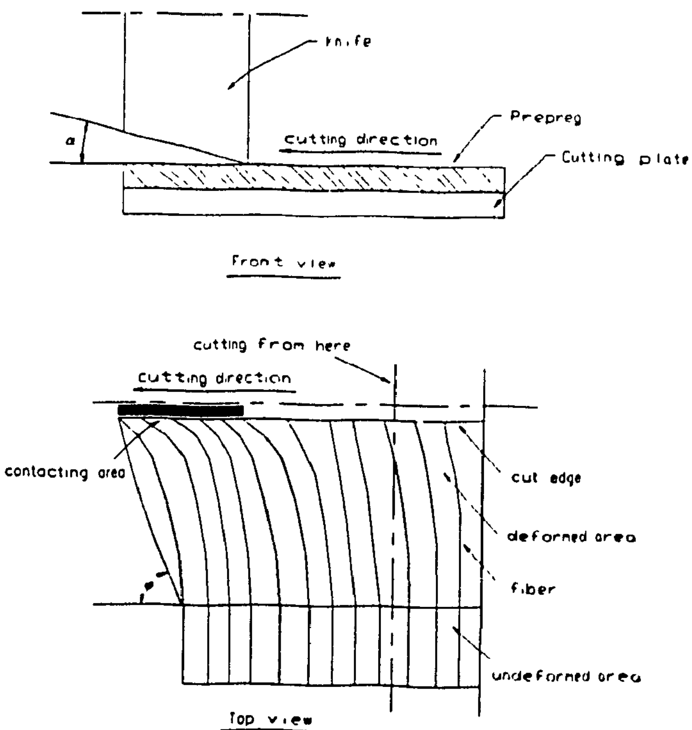

Figure 3.3 Schematic of fibre deflection in the contacting area between knife and prepreg

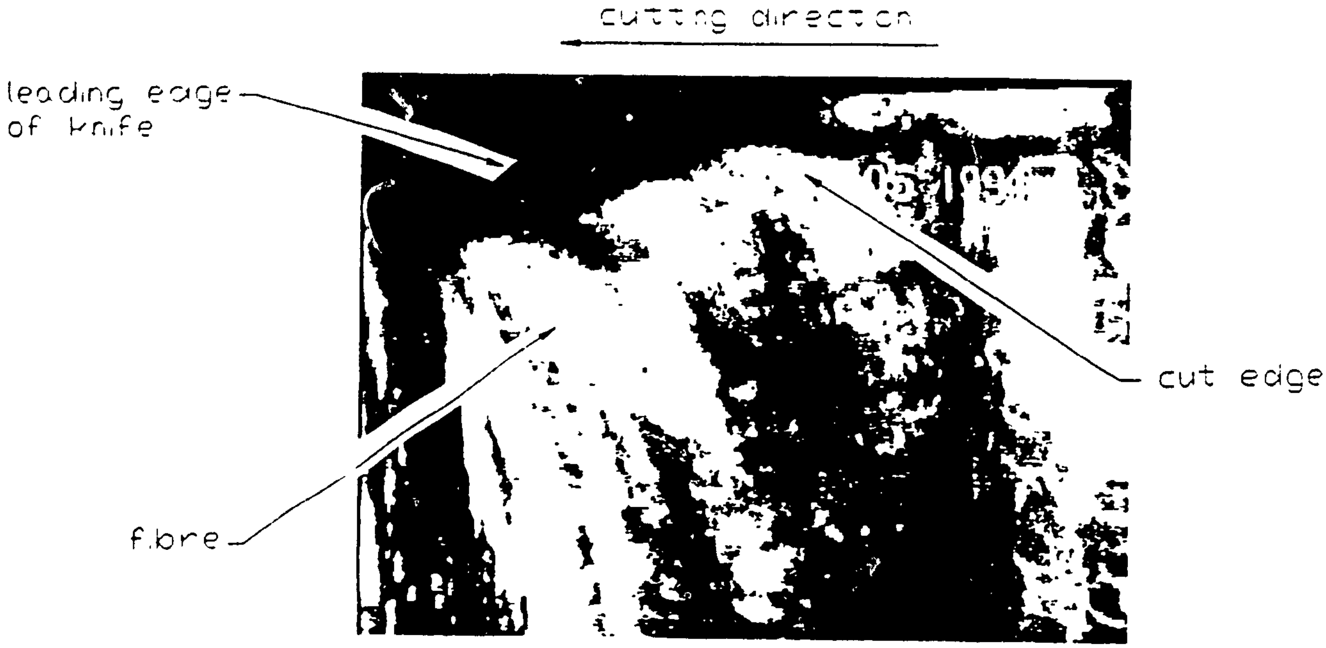

Figure 3.4 Photo showing the fibre deflection in the contacting area between knife and prepreg (condition: sharp knife with $\alpha = 60°$, aluminium plate backing)

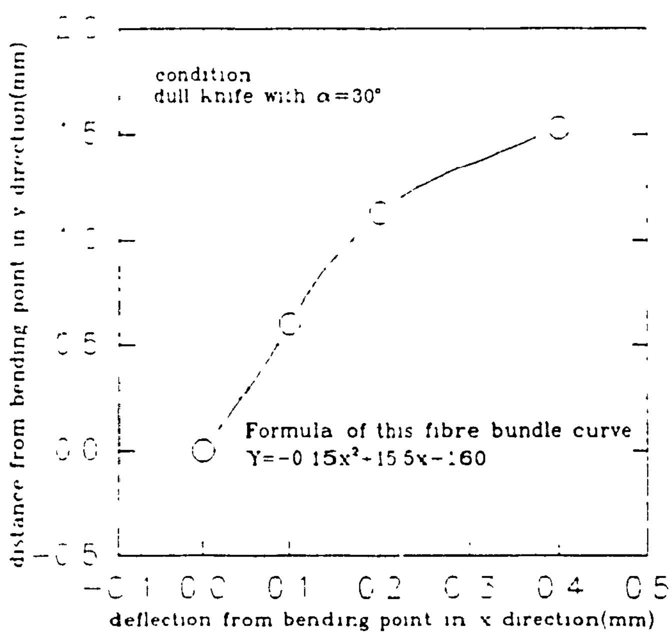

Figure 3.5 Fibre deflection in the contacting area (condition: dull knife with $\alpha = 30°$)

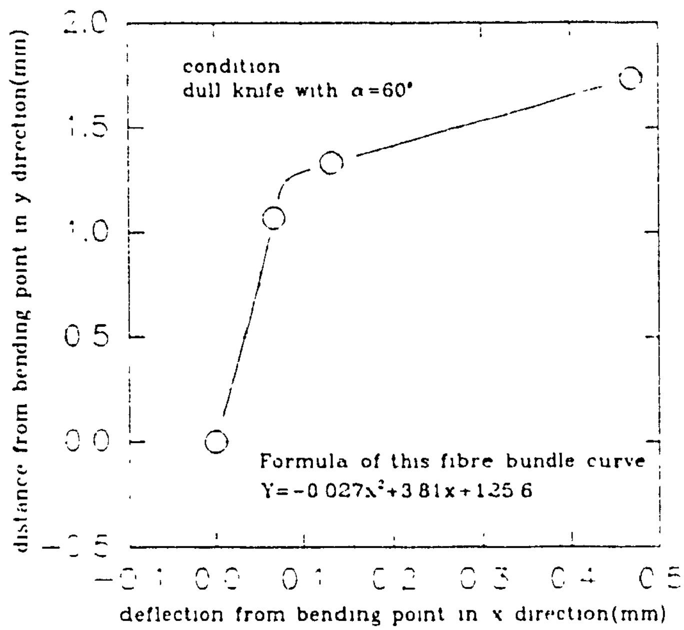

Figure 3.6 Fibre deflection in the contacting area (condition: dull knife with $\alpha = 60°$)

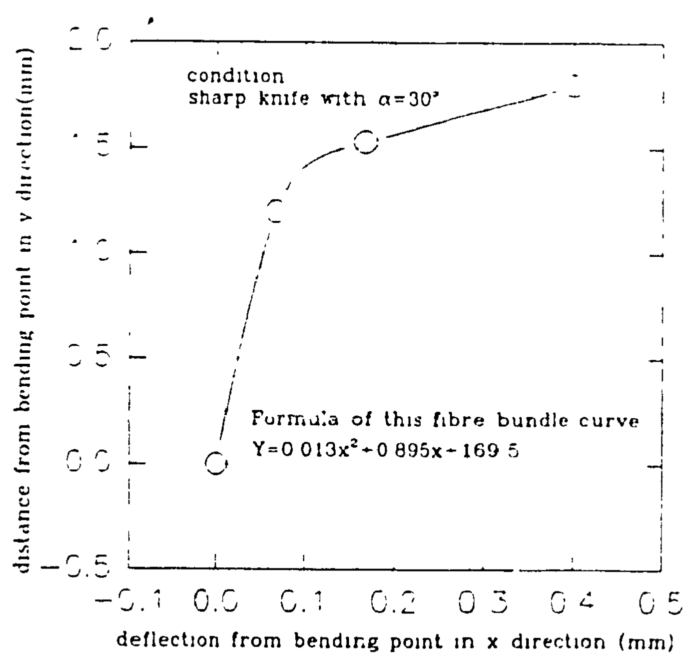

Figure 3.7 Fibre deflection in the contacting area (condition: sharp knife with $\alpha = 30°$)

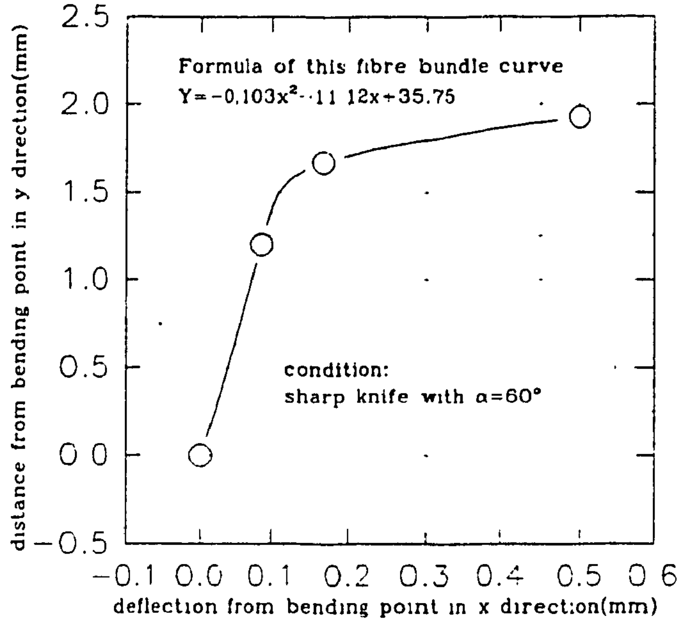

Figure 3.8 Fibre deflection in the contacting area (condition: sharp knife with $\alpha = 60^o$)

Figure 3.14 shows the time dependent behaviour of fibre bundle deflection. The results are presented in terms of δ=90° cutting using sharp knife with α=30°. It was found that the fibre deflection changes sharply from maximum deflection to normal deflection within 5 seconds. After that, there is no change of fibre deflection. Therefore, there is no obvious time dependent behaviour for unidirectional prepreg cutting.

The effect of cutting orientation to fibre direction on fibre deflection was shown in Figure 3.15. The cutting orientation to fibre direction for unidirectional prepreg cutting is shown in Figure 2.1. The fibre deflection was generated using sharp knife with α=30° for different types of backing. It is shown in Figure 3.15 that the cutting orientation with respect to fibre direction has effect on fibre deflection. When the cutting orientation to fibre direction δ is in the range between 0° and 90°, the stress at the cutting point of fibre is complicated. At this point, a shear stress component along the fibre direction appears. This enhances the eases for fibre break. Because the ultimate strength of fibre is constant, the tensile stress at the point of fibre break decreases due to the shear stress along the fibre direction which results in decrease of pulling force. The fibre deflection is directly proportional to the pulling force. Therefore, the fibre deflection decreases when the cutting orientation is not perpendicular to fibre direction.

The plot of fibre deflection versus primary knife angle α for unidirectional prepreg cutting using aluminum plate is shown in Figure 3.16. From this figure, as the primary knife angle α increases from 30° to 60°, the fibre deflection increases a little for sharp knife. However, as the primary knife angle α increases from 30° to 60°, the fibre deflection decreases for dull knife. This may be due to squeezing when the dull knife with $\alpha=60^\circ$ was used. In chapter 2, it was known that the variation of primary knife angle α has nothing to do with pulling force F_2. Since fibre deflection is directly proportional to pulling force, the primary knife angle α has no significant effect on the fibre deflection. It is also known that the larger the primary knife angle α, the better the cutting performance. Therefore, for "one cut", the knife with $\alpha=60^\circ$ is a better choice.

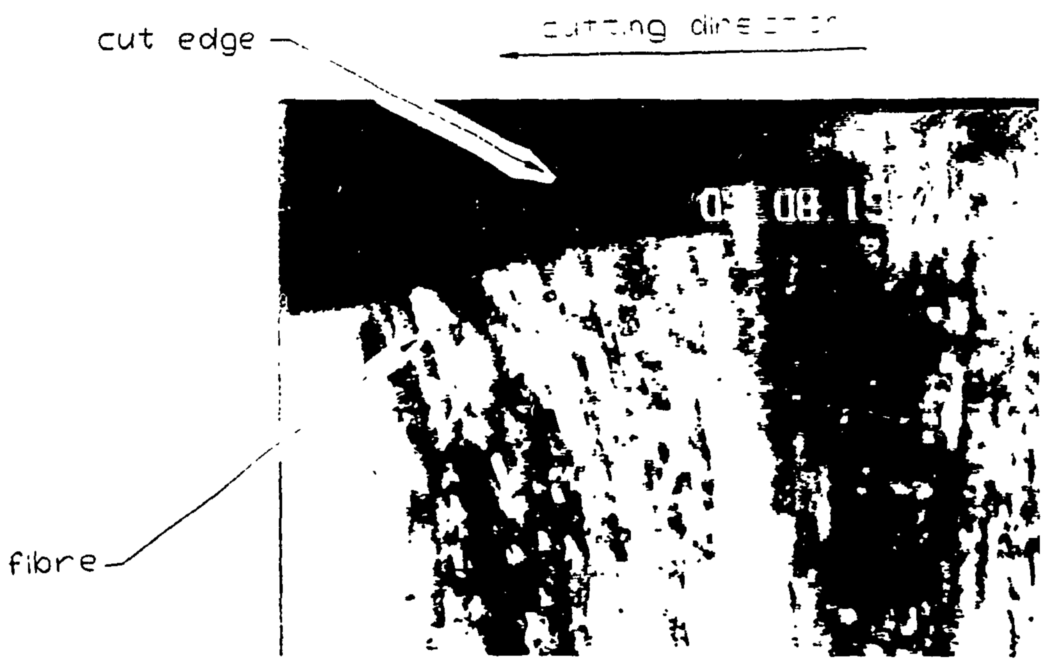

Figure 3.9 Photo showing the fibre deflection after cutting for unidirectional prepreg (condition: sharp knife with $\alpha = 60°$, aluminium plate backing)

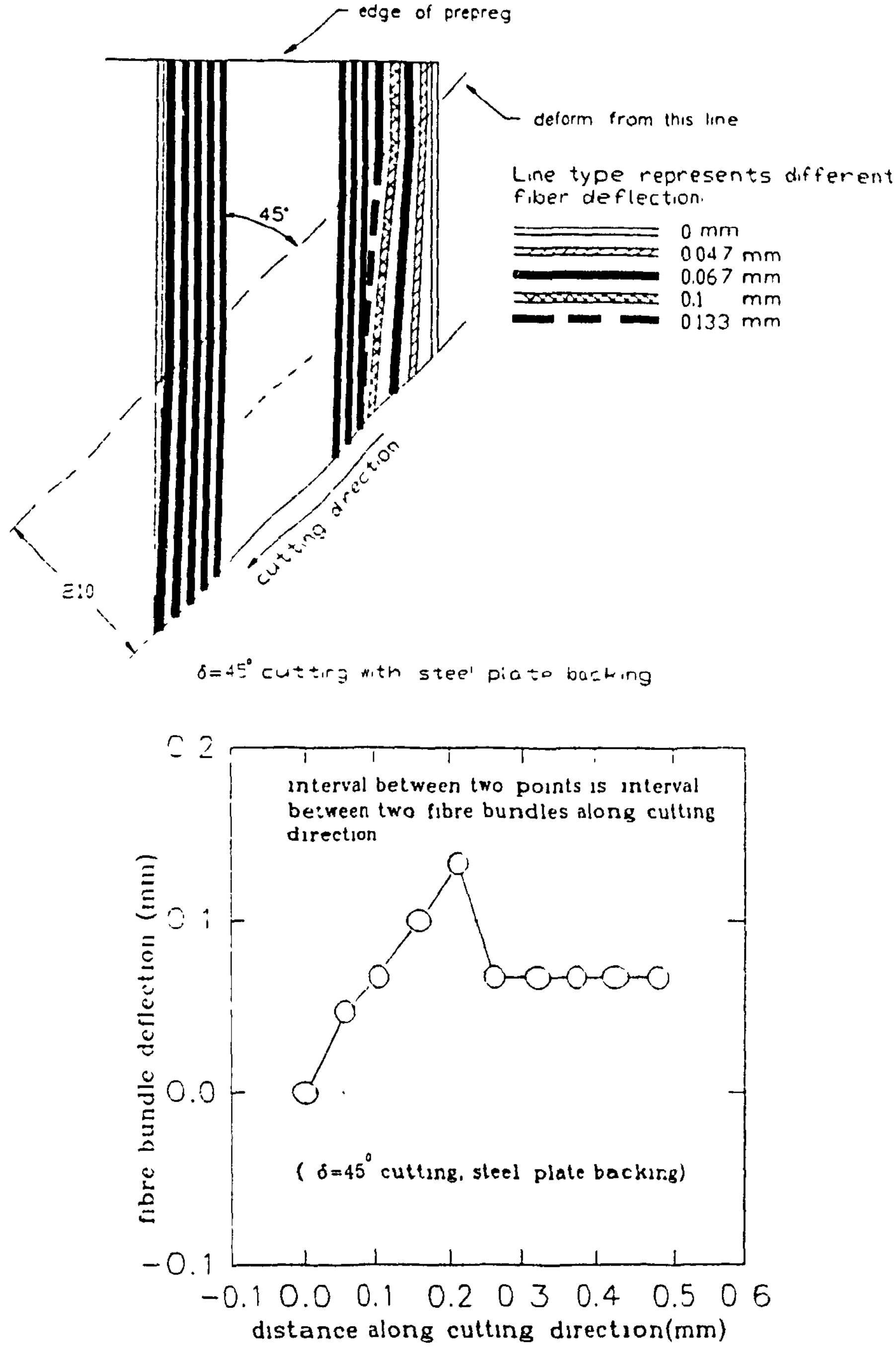

Figure 3.10 Fibre deflection after cutting of δ=45° cutting with steel plate backing

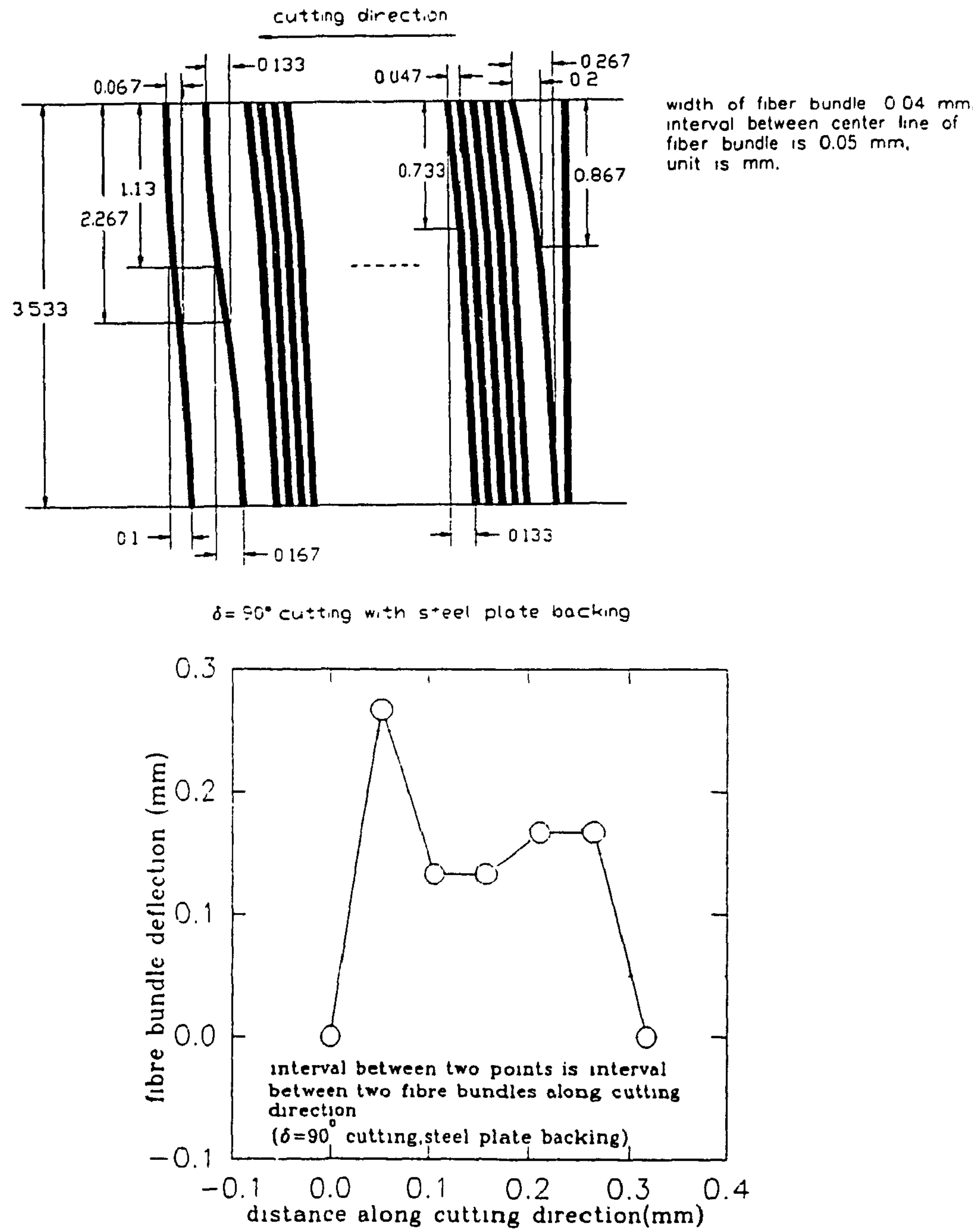

Figure 3.11 Fibre deflection after cutting of δ=90° cutting with steel plate backing

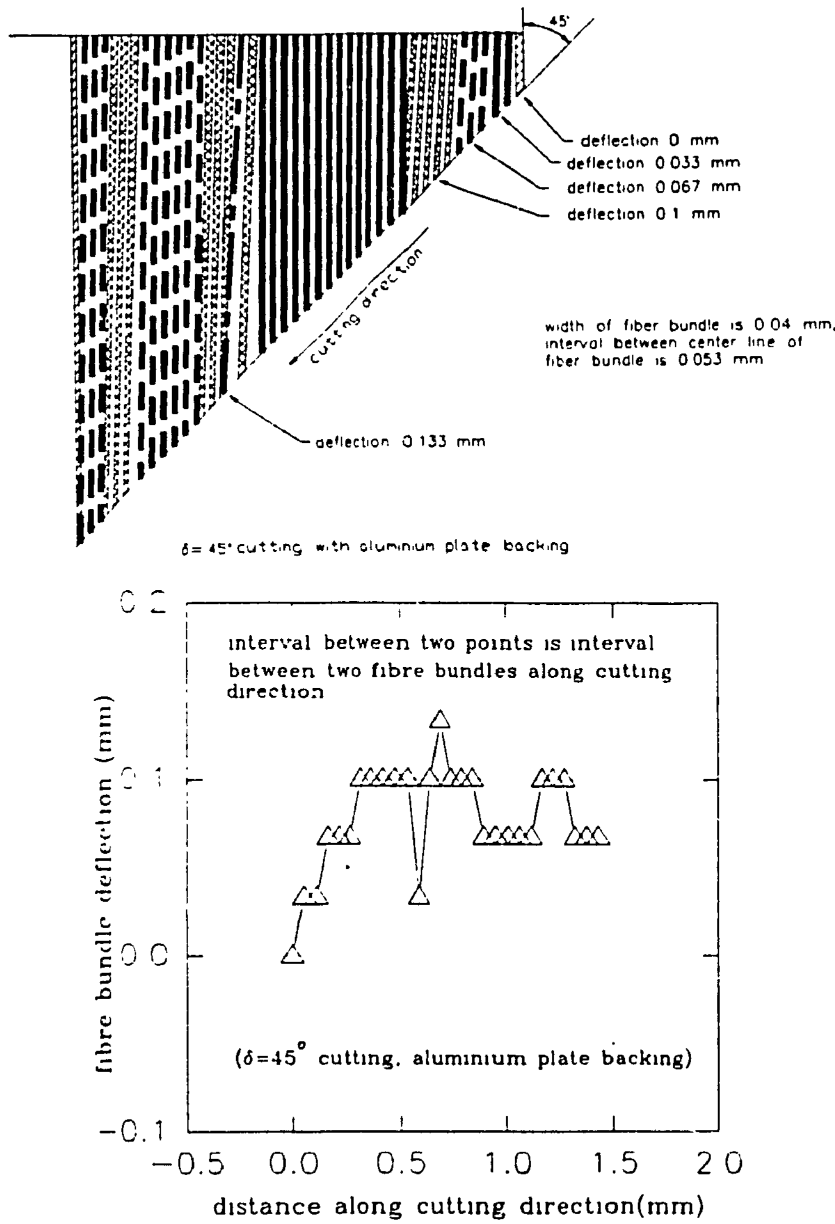

Figure 3.12 Fibre deflection after cutting of δ=45° cutting with aluminium plate backing

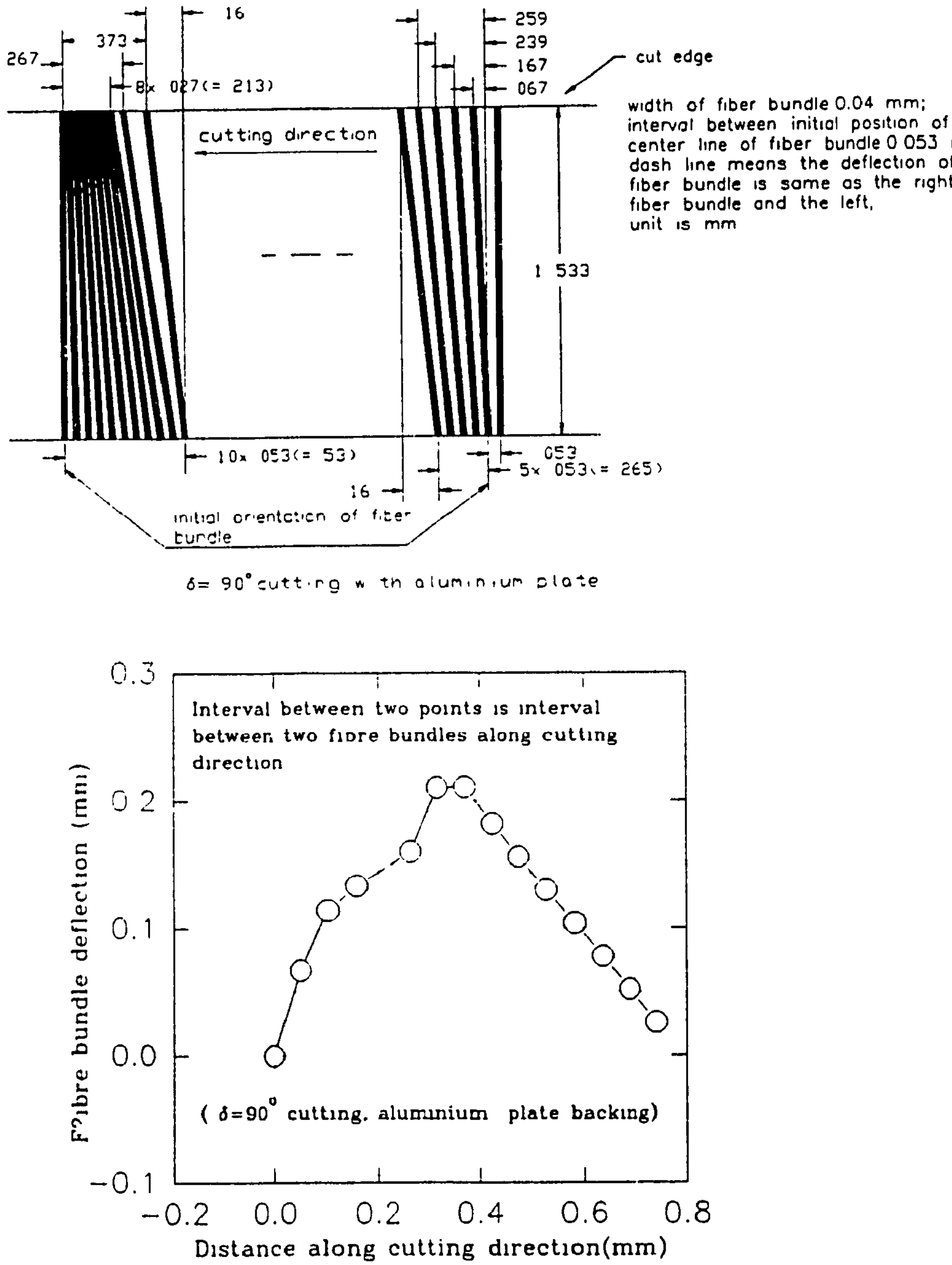

Figure 3.13 Fibre deflection after cutting of δ=90° cutting with aluminium plate backing

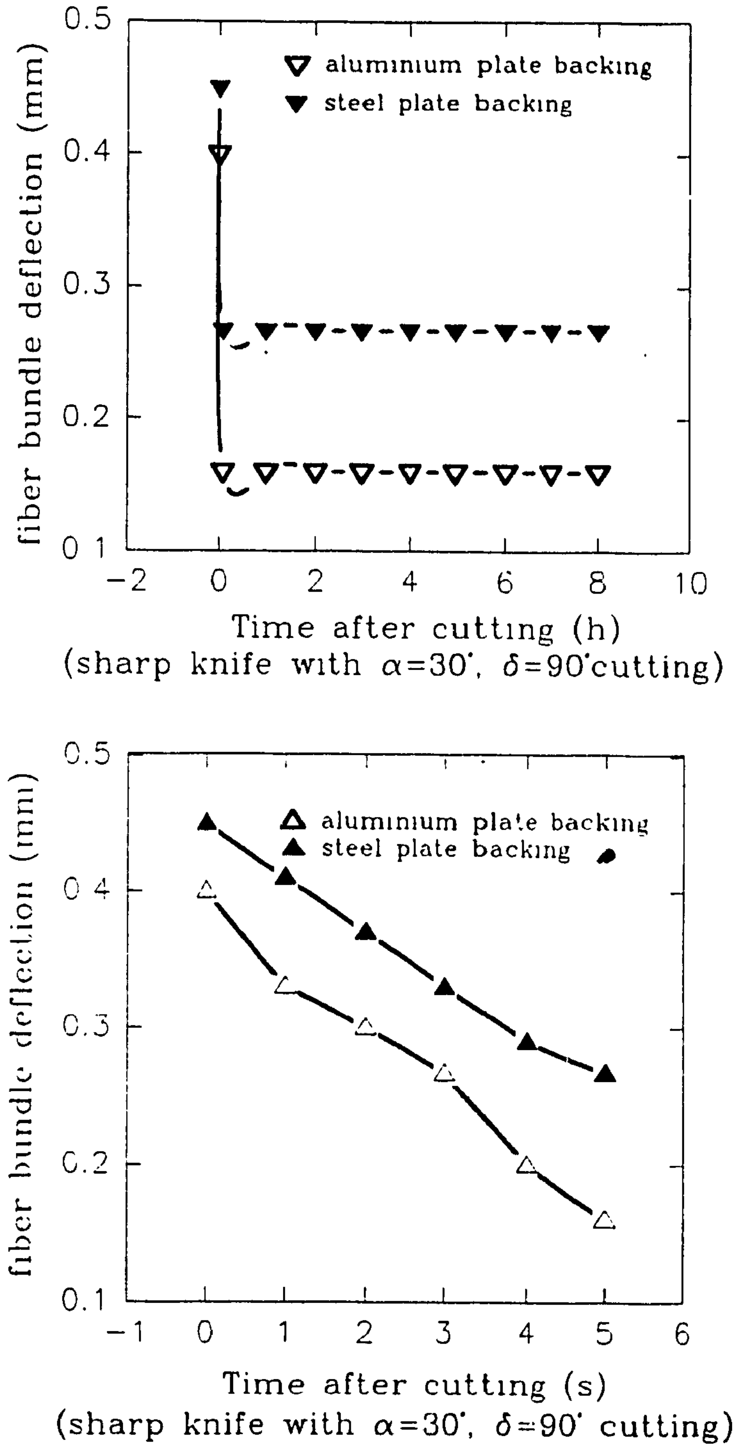

Figure 3.14 Time dependent behaviour of fibre deflection for unidirectional prepreg cutting

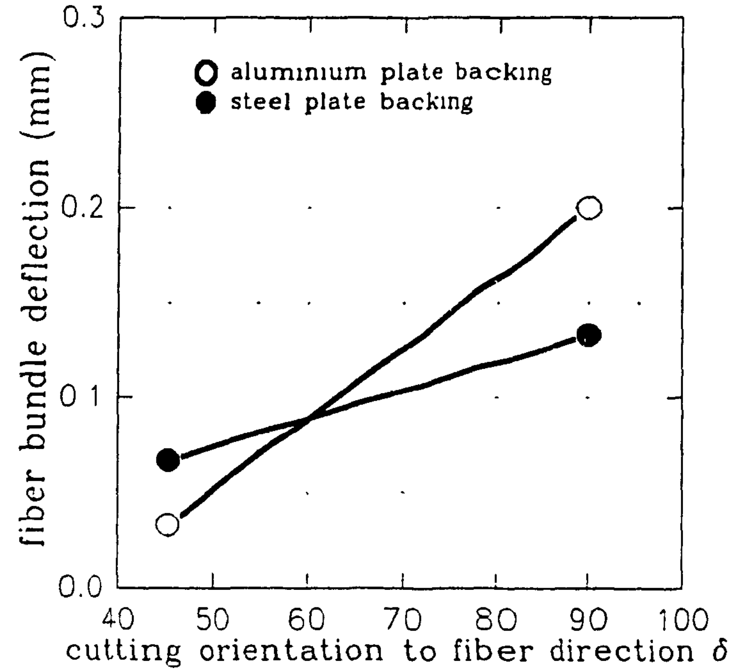

Figure 3.15 Effect of cutting orientation to fibre direction for unidirectional prepreg cutting

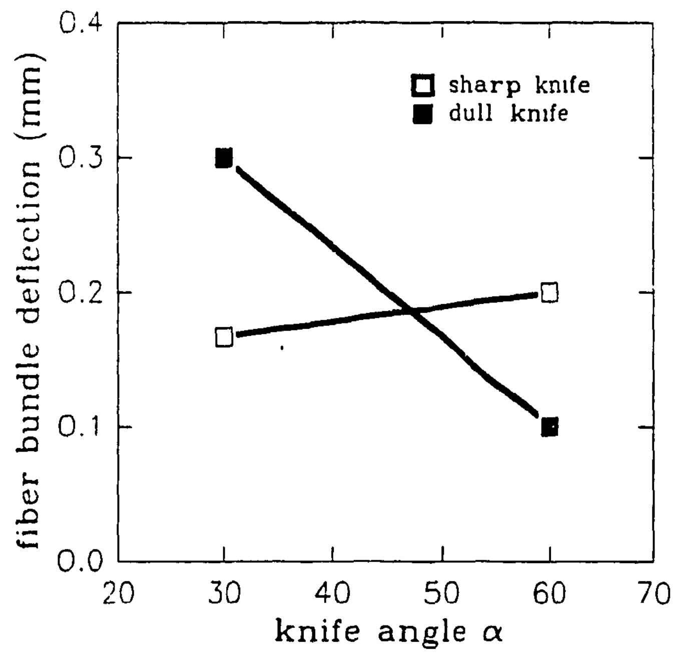

Figure 3.16 Effect of knife angle α on fibre deflection for unidirectional prepreg cutting

3.3 Fibre Deflection of Woven Prepreg due to Cutting

Woven fabric prepregs are one of the most widely used fibre reinforced resin forms. Fabrics typically offer flexibility in fabrication technique. Fibres can be woven into many

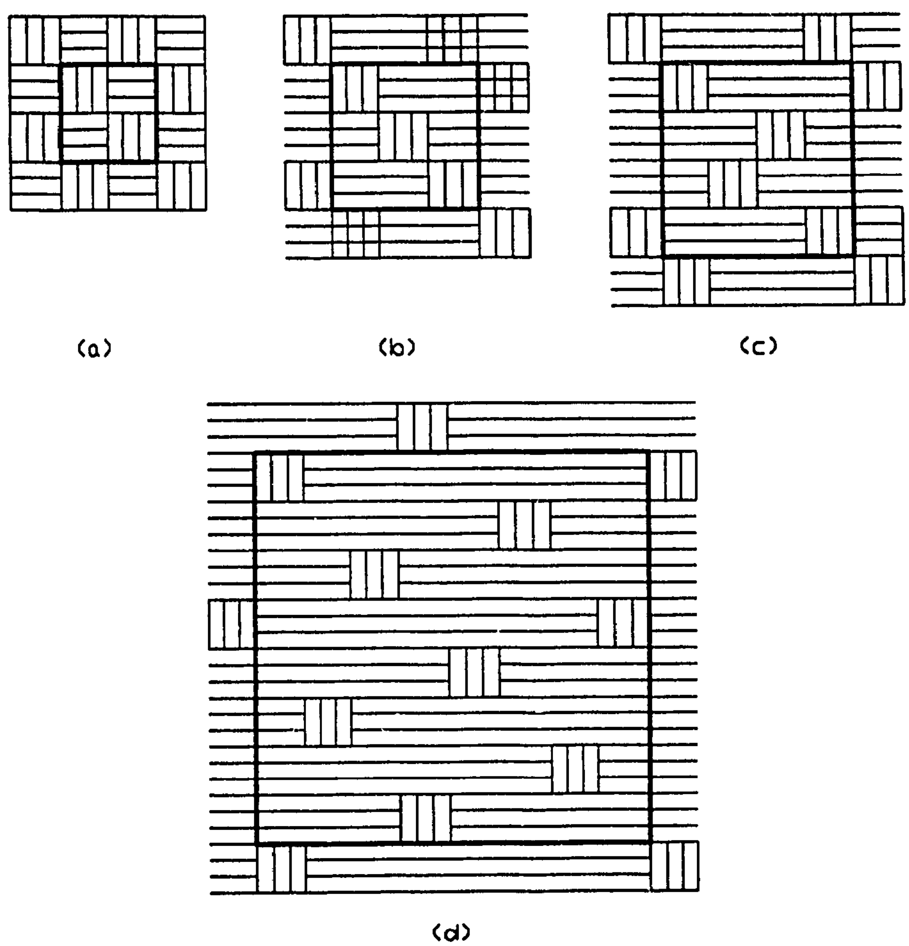

Figure 3.17 Examples of interlacing patterns in woven fabric (a) plain weave (n_g=2); (b) twill weave (n_g=3); (c) 4 harness satin (n_g=4); and (d) 8 harness satin (n_g=8). boldline indicates a basic two-dimensional repeated unit.

different types of weave patterns, widths and thickness. A two-dimensional fabric is woven by two sets of interlaced threads or yarns known as warp and fill threads. The types of fabrics can be categorized by both the geometrical and material patterns of repeat of the interlaced regions as shown in Figure 3.17.

3.3.1 Experimental

A composite prepreg was chosen in this study: 4 harness satin woven prepreg (MIL-B-131H, a commercial graphite epoxy woven prepreg from Bell Fibre Product Inc.) shown in Figure 3.17. The cutting knife used in this experiment is made from steel [Brand name: MASTERCRAFT Utility Knife]. The knife was operated by hand. Both sharp knife and dull knife were used in the experiment. The edge of sharp knife is 5 μm. The edge of dull knife is 75 μm. The experimental set up used in this experiment is exactly same as one in section 3.2.1 and is shown in Figure 3.2. The fibre deflection was magnified by telescope and image was shown on the screen of monitor through camera adapter. The fibre deflection can be measured on the screen of monitor. The magnification for measuring the woven prepreg is 50. An optical microscope was used to verify the results later on.

3.3.2 Fibre Deflection in the Contacting Area between Knife and Woven Prepreg

The fibre deflection in the contacting area between knife and woven prepreg was observed on TV screen which is connected to telescope QUESTAR QM1. The sharp knife and dull knife with primary knife angle $\alpha = 30^o$ and 60^o were used to investigate their effect on fibre deflection of woven prepreg. The formulas were set up to express the fibre curvatures. In order to create these equations, a coordinate system was established and is shown in the figure. The original point of this coordinate system is located at the bending point of fibre. Using this coordinate system, three points on the deflected fibre were measured. (X,Y) values of these points are, then, used in equation $Y=aX^2+bX+c$ and the coefficients of curvature equations can be determined. Figures 3.18 to 3.24 show the fibre deflection and its curvature formula in the contacting area between knife and woven prepreg for the following cases:

- **$\delta = 45^o$ cutting under the conditions:**

1. sharp knife with $\alpha = 30^o$, aluminum plate backing
2. sharp knife with $\alpha = 30^o$, steel plate backing

- **$\delta = 90^o$ cutting under the conditions:**

3. sharp knife with $\alpha = 30^o$, aluminum plate backing
4. sharp knife with $\alpha = 30^o$, steel plate backing
5. sharp knife with $\alpha = 60^o$, aluminum plate backing
6. dull knife with $\alpha = 30^o$, aluminum plate backing
7. dull knife with $\alpha = 60^o$, aluminum plate backing

3.3.3 Fibre Deflection of Woven Prepreg after Cutting

Using the same knife, monitor system and coordinate system in 3.2.1, the fibre deflection after cutting of woven prepreg was observed. The photo showing the fibre deflection after cutting of woven prepreg for the case ($\delta = 90^{o}$ cutting with the condition: sharp knife with $\alpha = 30^{o}$, aluminium plate backing) is shown in Figure 3.25 and the magnification of this photo is 50. The fibre deflection and its curvature equation after cutting of woven prepreg for the following cases are shown in Figure 3.26 to Figure 3.37.

- **$\delta = 45^{o}$ cutting under the conditions:**

1. sharp knife with $\alpha = 30^{o}$, aluminum plate backing
2. sharp knife with $\alpha = 30^{o}$, steel plate backing

- **$\delta = 90^{o}$ cutting under the conditions:**

3. sharp knife with $\alpha = 30^{o}$, aluminum plate backing
4. sharp knife with $\alpha = 30^{o}$, steel plate backing
5. sharp knife with $\alpha = 30^{o}$, aluminum plate backing
6. dull knife with $\alpha = 30^{o}$, aluminum plate backing
7. dull knife with $\alpha = 30^{o}$, aluminum plate backing

Figure 3.38 shows the time dependent behaviour of woven prepreg after cutting for above cases. Among these cases of $\delta = 90^{o}$ cutting, it is usual that fibre deflection changes sharply from maximum deflection to permanent deflection within 5 seconds. After that, there is no change of fibre deflection. The only exception among them is the case: sharp knife, aluminium backing plate, knife with $\alpha = 30^\circ$, and the fibre deflection changes from 0.6 mm to 0.2 mm within 2 hours. For $\delta = 45^\circ$ cutting, obvious fibre deflection exists and fibre deflection varies from 3.4 mm to 1.2 mm within 2 hours.

The effect of cutting orientation to fibre direction on fibre permanent deflection was also investigated and shown in Figure 3.39. The cutting orientation to fibre direction is shown in Figure 2.1. The experimental condition is using sharp knife with $\alpha = 30^\circ$ for different backing (aluminium plate and steel plate). It is shown in Figure 3.39 that the cutting orientation to fibre direction has effect on fibre deflection.

The plot of fibre deflection versus primary knife angle α for woven prepreg cutting is shown in Figure 3.40. It is can be seen that the fibre deflection when using knife with $\alpha = 60^\circ$ is larger than one when using knife with $\alpha = 30^\circ$. However, the difference between them is larger than one in the case of unidirectional prepreg cutting. The reason is that the elastic modulus of foundation for woven prepreg cutting is much smaller than unidirectional prepreg cutting due to its loose structure.

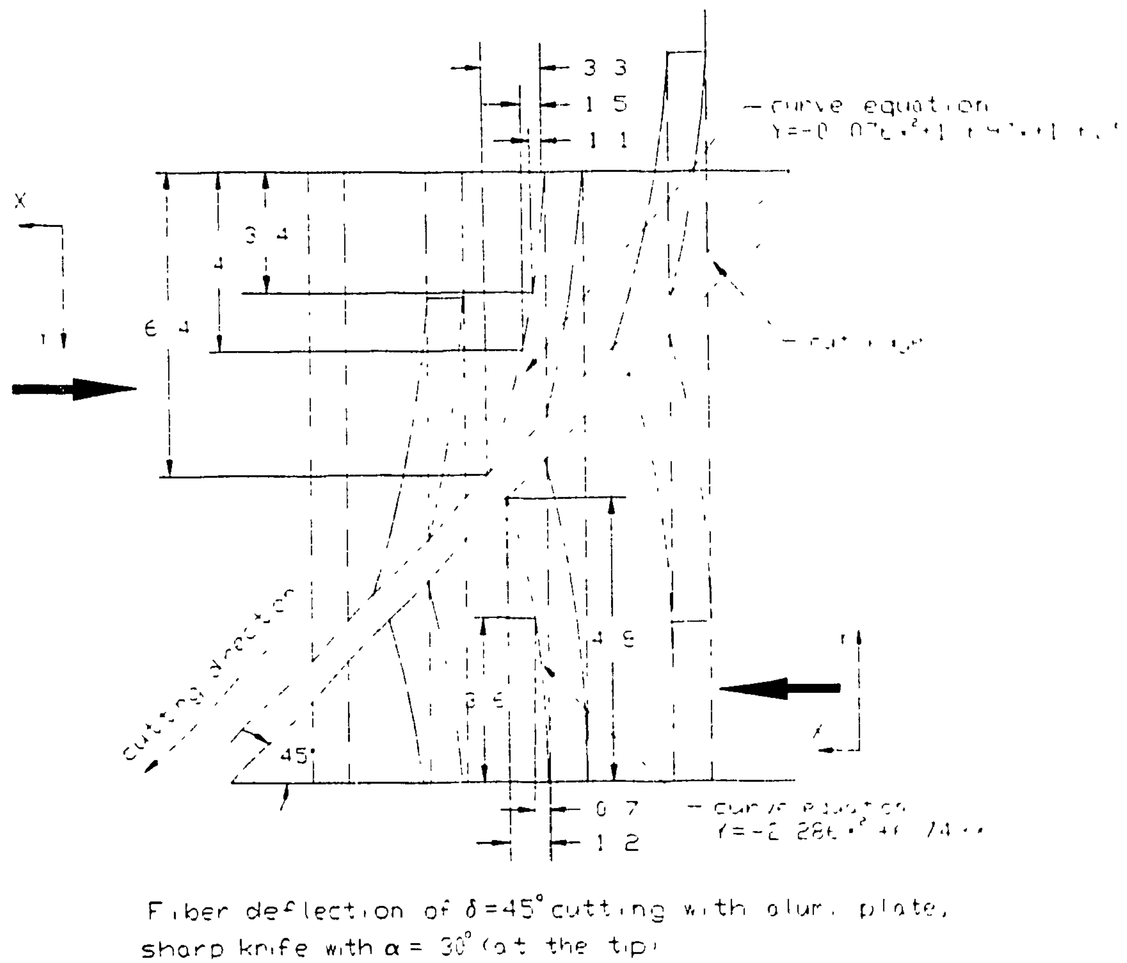

Figure 3.18 Fibre deflection in the contacting area for δ=45° cutting of woven prepreg (condition: sharp knife with $\alpha = 30°$, aluminum plate backing)

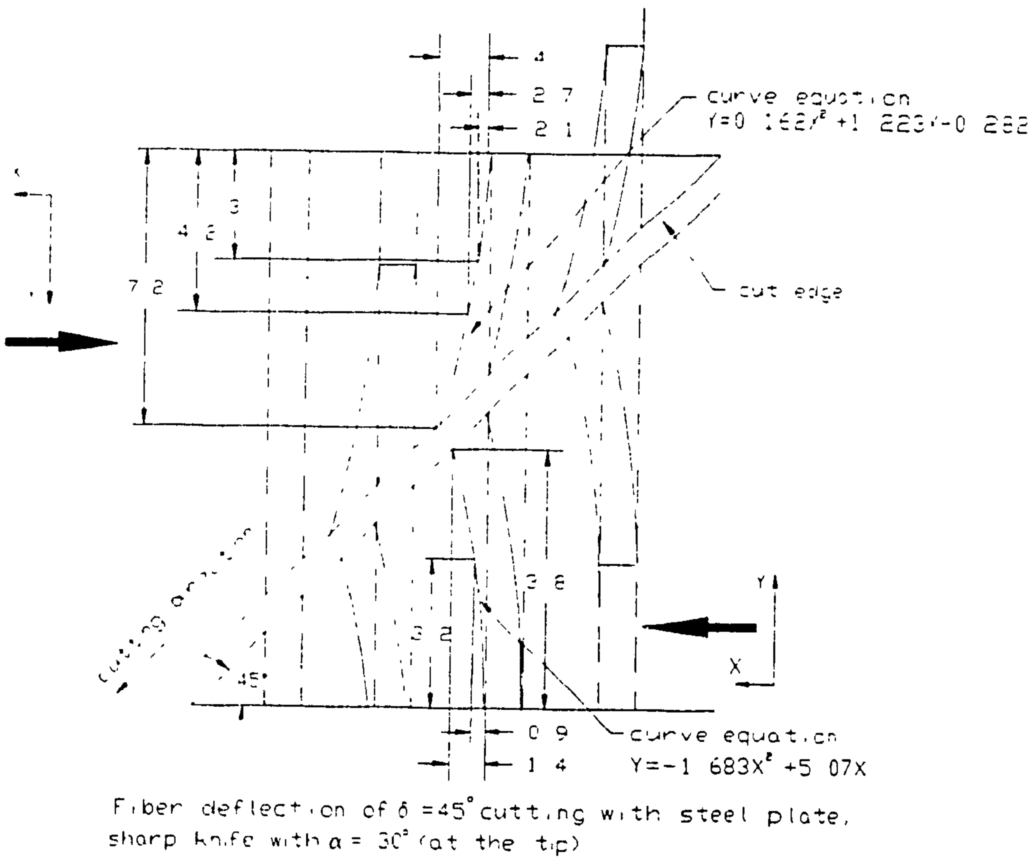

Figure 3.19 Fibre deflection in the contacting area for δ=45° cutting of woven prepreg (condition: sharp knife with α = 30°, steel plate backing)

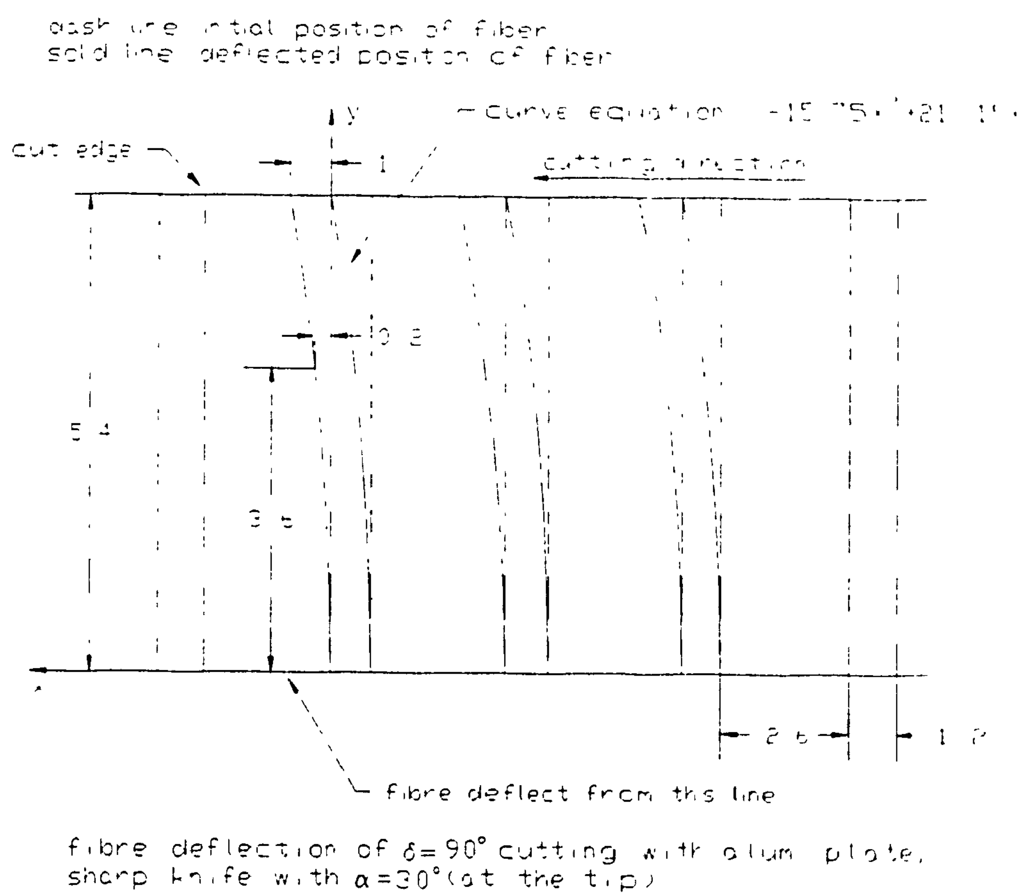

Figure 3.20 Fibre deflection in the contacting area for δ=90° cutting of woven prepreg (condition: sharp knife with α = 30°, aluminium plate backing)

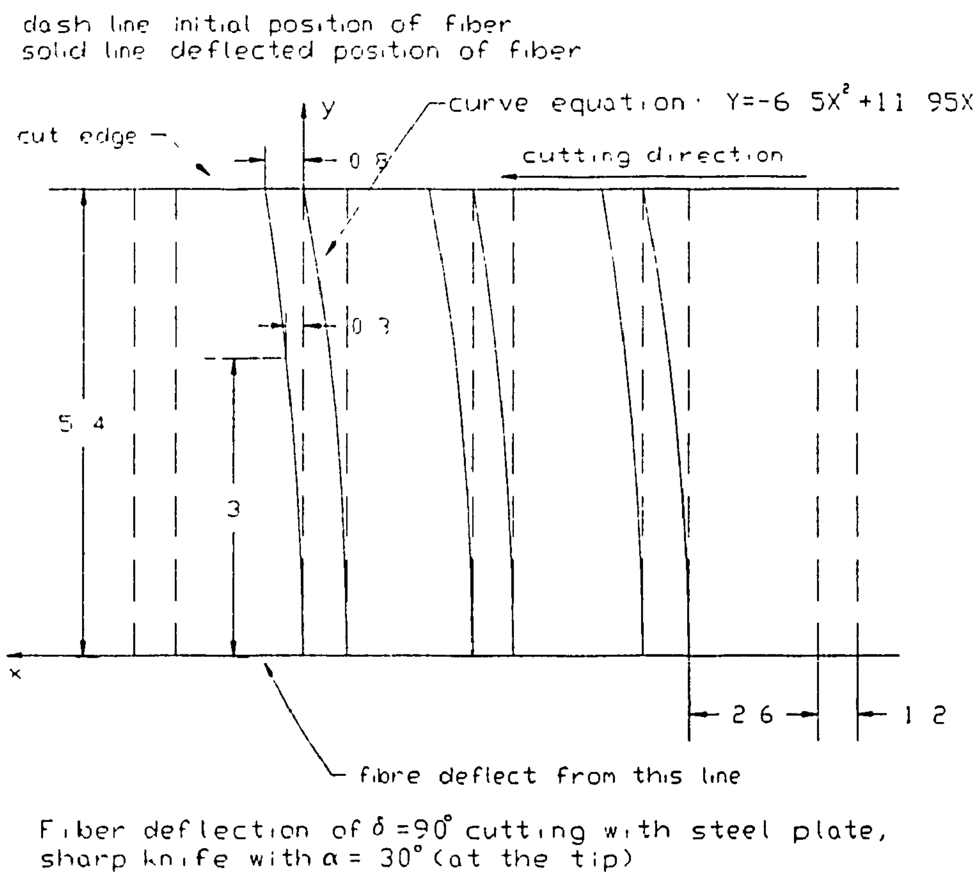

Figure 3.21 Fibre deflection in the contacting area for δ=90° cutting of woven prepreg (condition:sharp knife with α = 30°, steel plate backing)

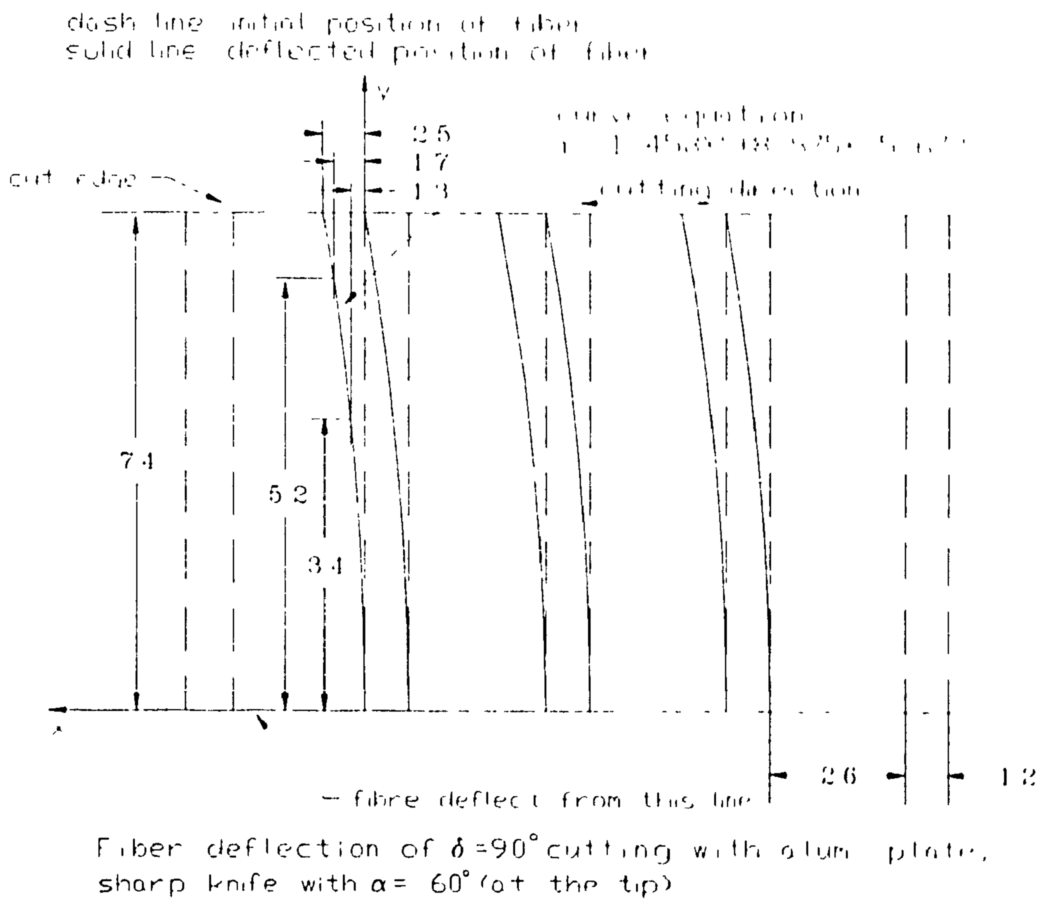

Figure 3.22 Fibre deflection in the contacting area for δ=90° cutting of woven prepreg (condition:sharp knife with α = 60°, aluminum plate backing)

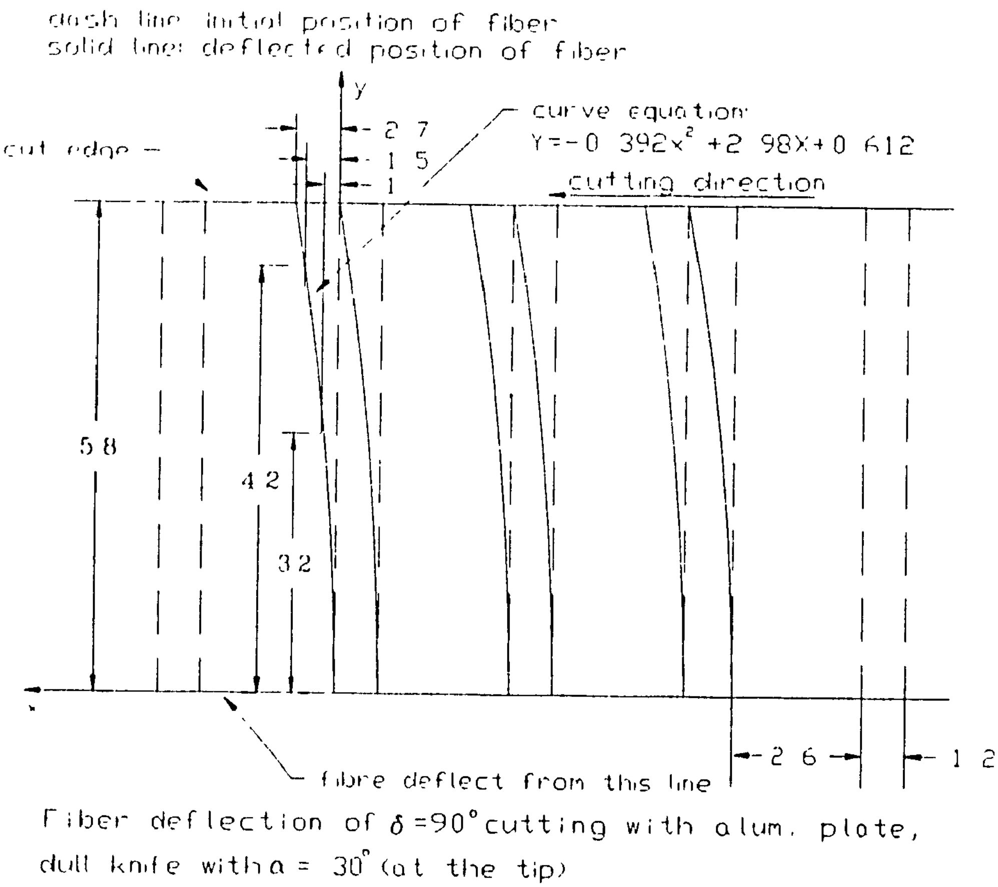

Figure 3.23 Fibre deflection in the contacting area for δ=90° cutting of woven prepreg (condition:dull knife with α = 30°, aluminum plate backing)

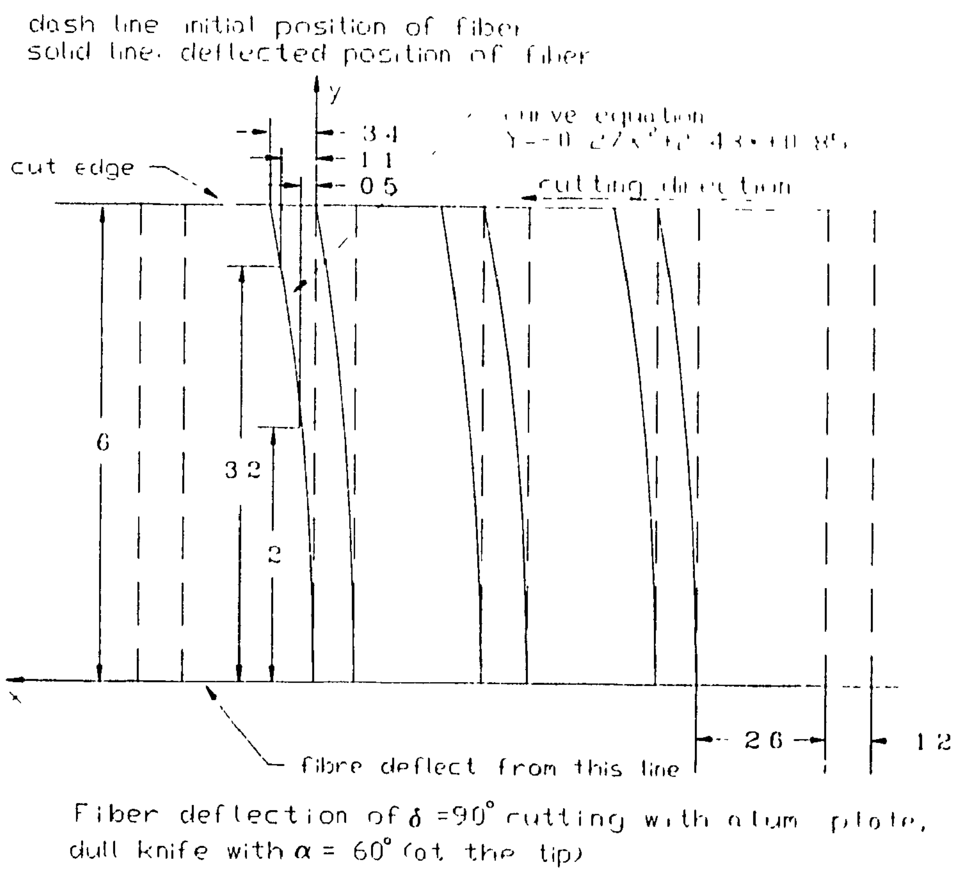

Figure 3.24 Fibre deflection in the contacting area for δ=90° cutting of woven prepreg (condition: dull knife with α = 60°, aluminum plate backing)

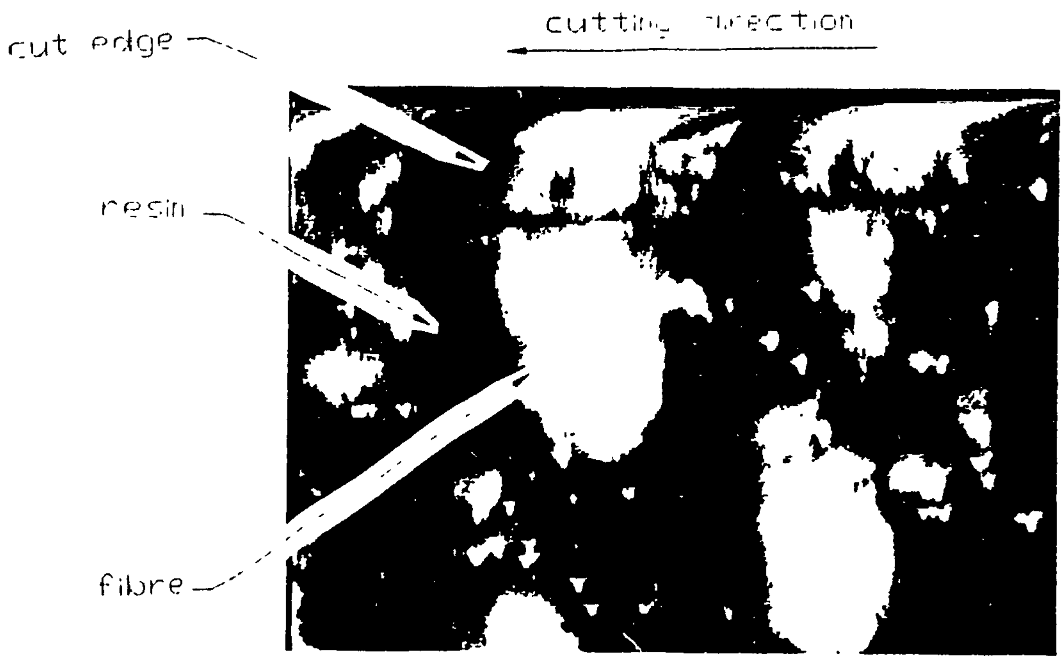

Figure 3.25 Photo of fibre deflection for δ=90° cutting of woven prepreg
(condition: sharp knife with α = 30°, aluminium plate backing)

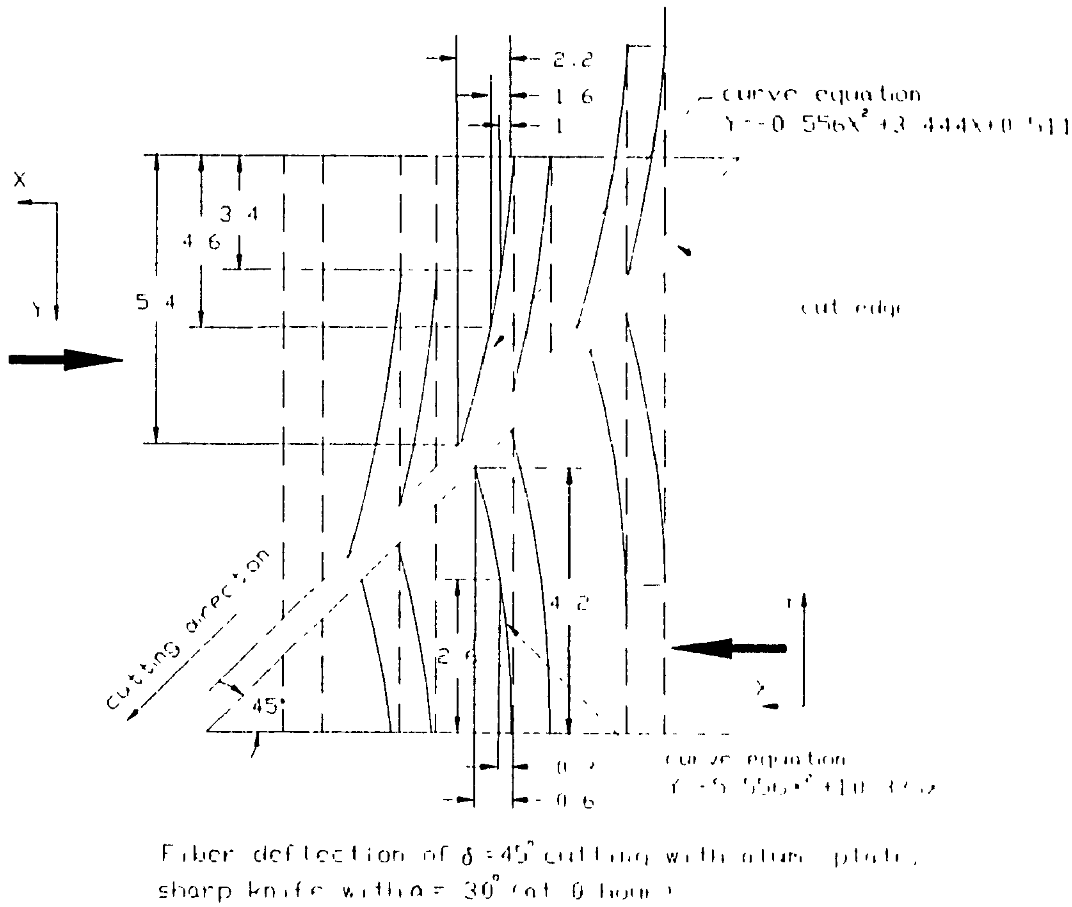

Figure 3.26 Fibre deflection at 0 hour for δ=45° cutting of woven prepreg

(condition: sharp knife with α = 30°, aluminum plate backing)

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* 0 hour means 1 minutes after knife pass away the cut edge

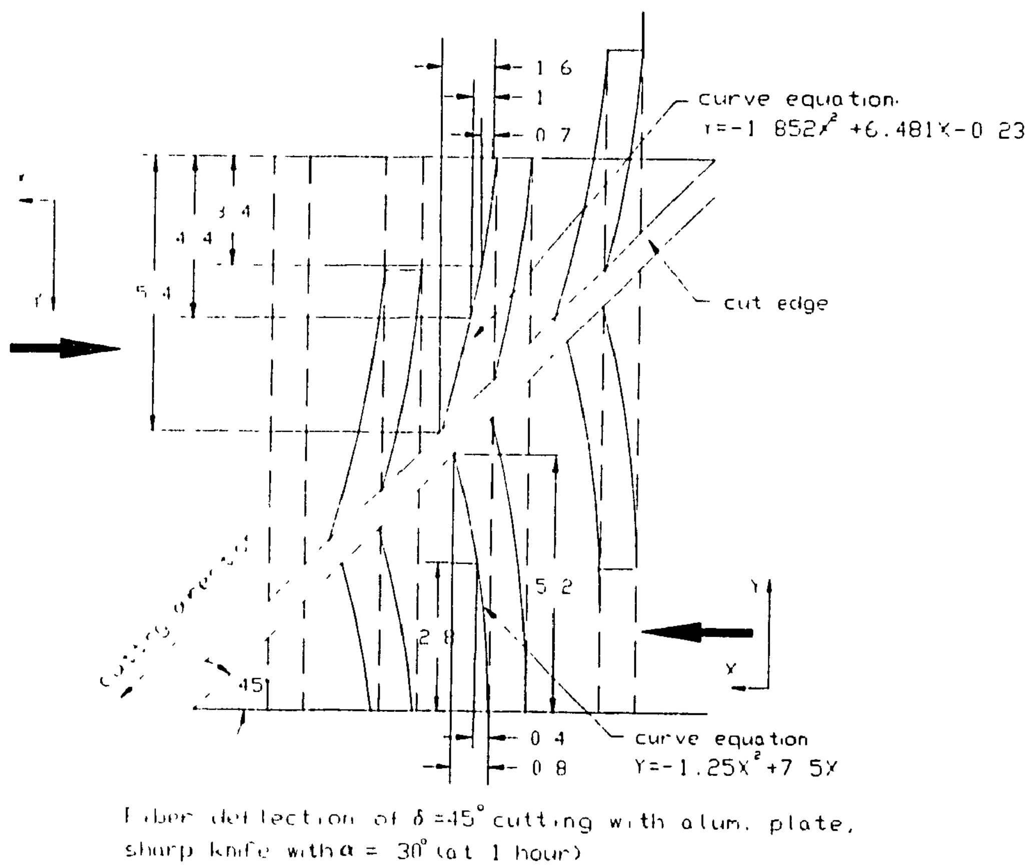

Figure 3.27 Fibre deflection at 1 hour for δ=45° cutting of woven prepreg (condition: sharp knife with $\alpha = 30°$, aluminum plate backing)

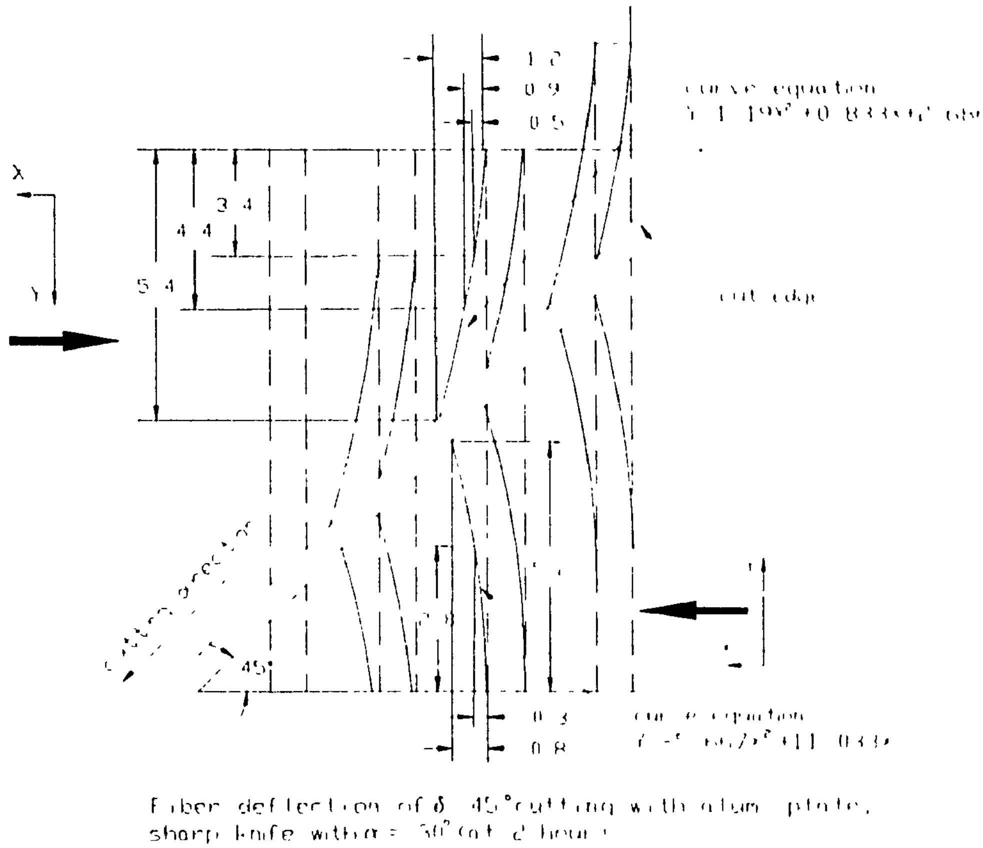

Figure 3.28 Fibre deflection at 2 hour for $\delta=45^{\circ}$ cutting of woven prepreg (condition: sharp knife with $\alpha = 30^{\circ}$, aluminum plate backing)

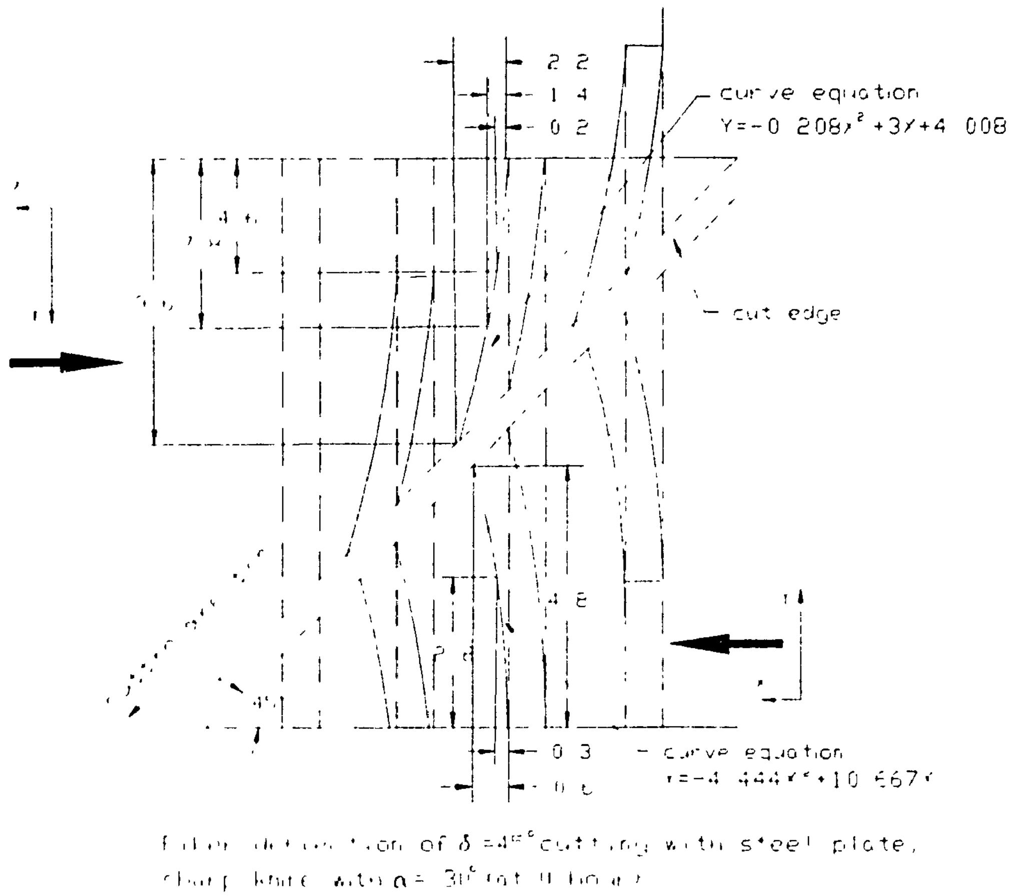

Figure 3.29 Fibre deflection at 0 hour for δ=45° cutting of woven prepreg

(condition: sharp knife with $\alpha = 30^{\circ}$, steel plate backing)

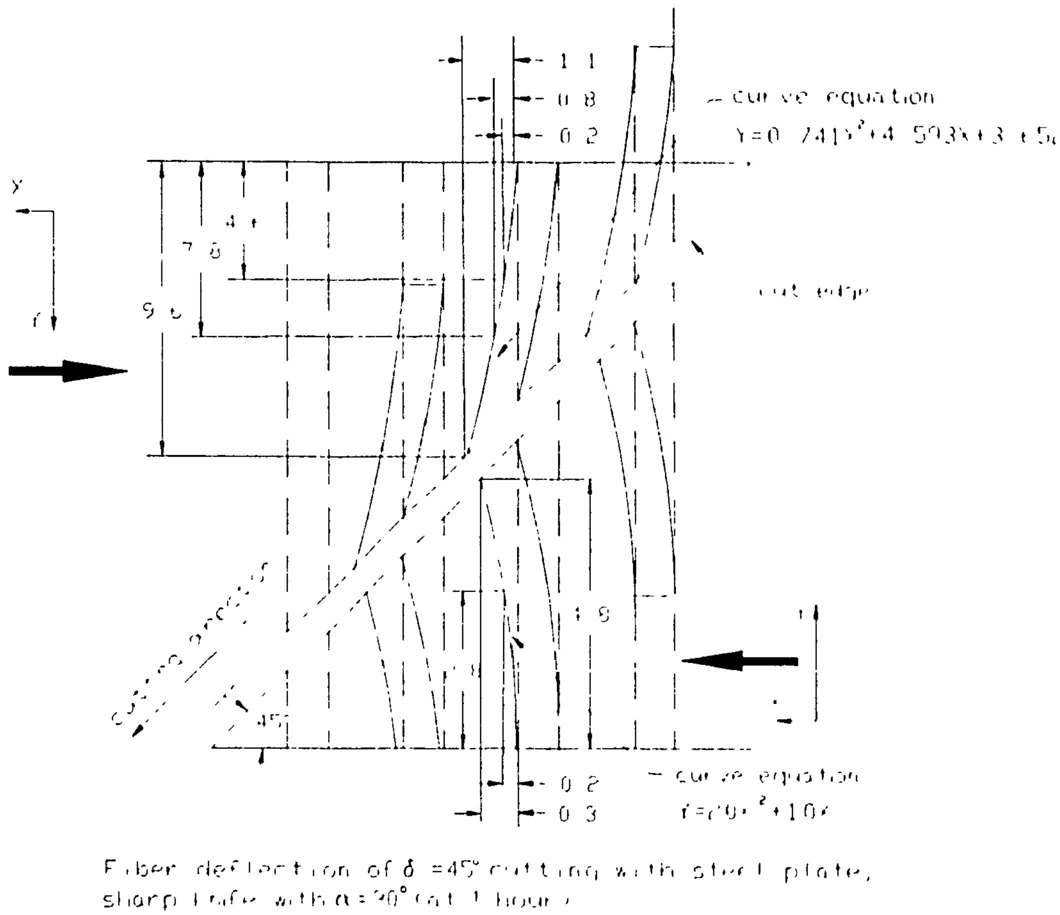

Figure 3.30 Fibre deflection at 1 hour for δ=45° cutting of woven prepreg

(condition: sharp knife with α = 30°, steel plate backing)

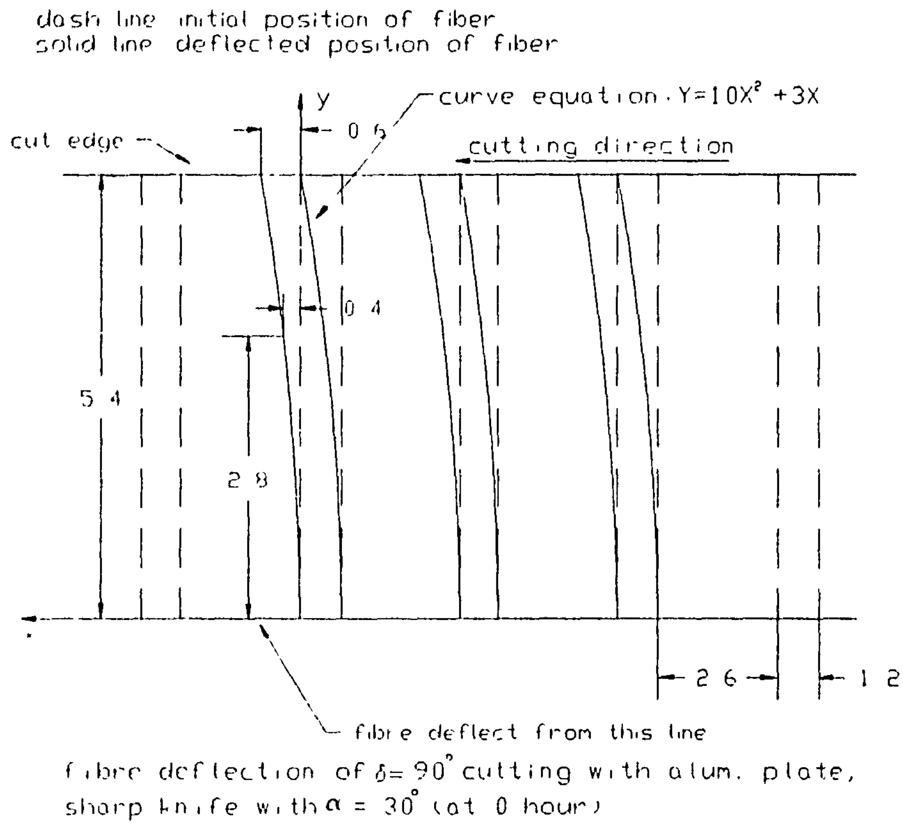

Figure 3.31 Fibre deflection at 0 hour for δ=90° cutting of woven prepreg

(condition: sharp knife with $\alpha = 30°$, aluminum plate backing)

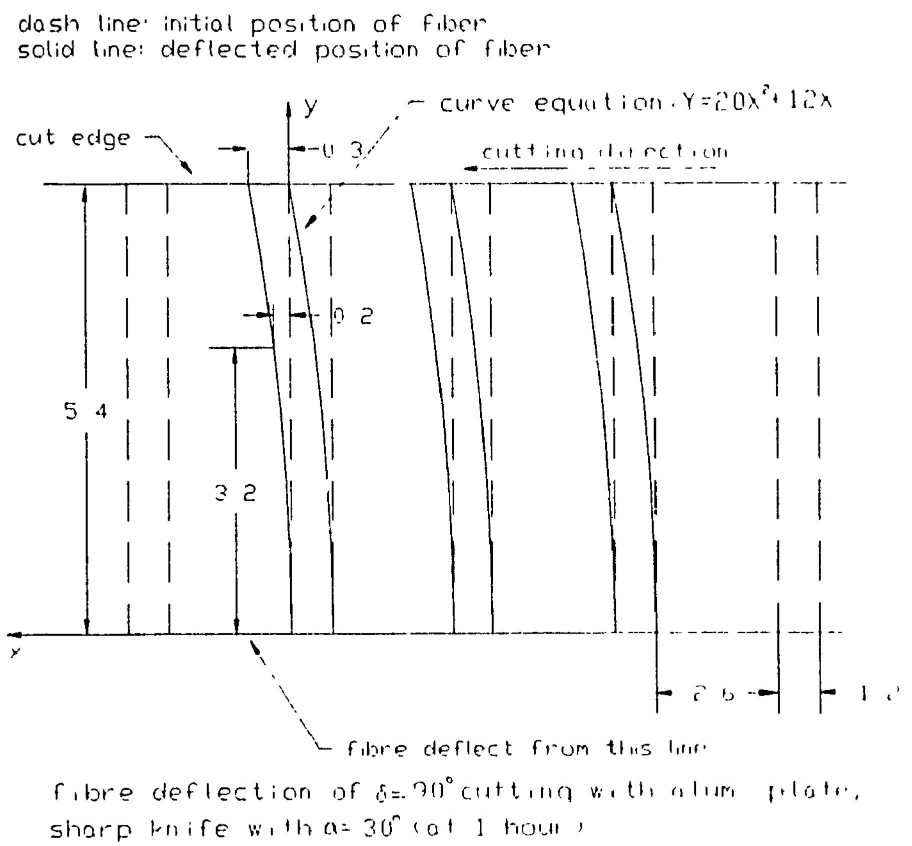

Figure 3.32 Fibre deflection at 1 hour for δ=90° cutting of woven prepreg

(condition: sharp knife with α = 30°, aluminum plate backing)

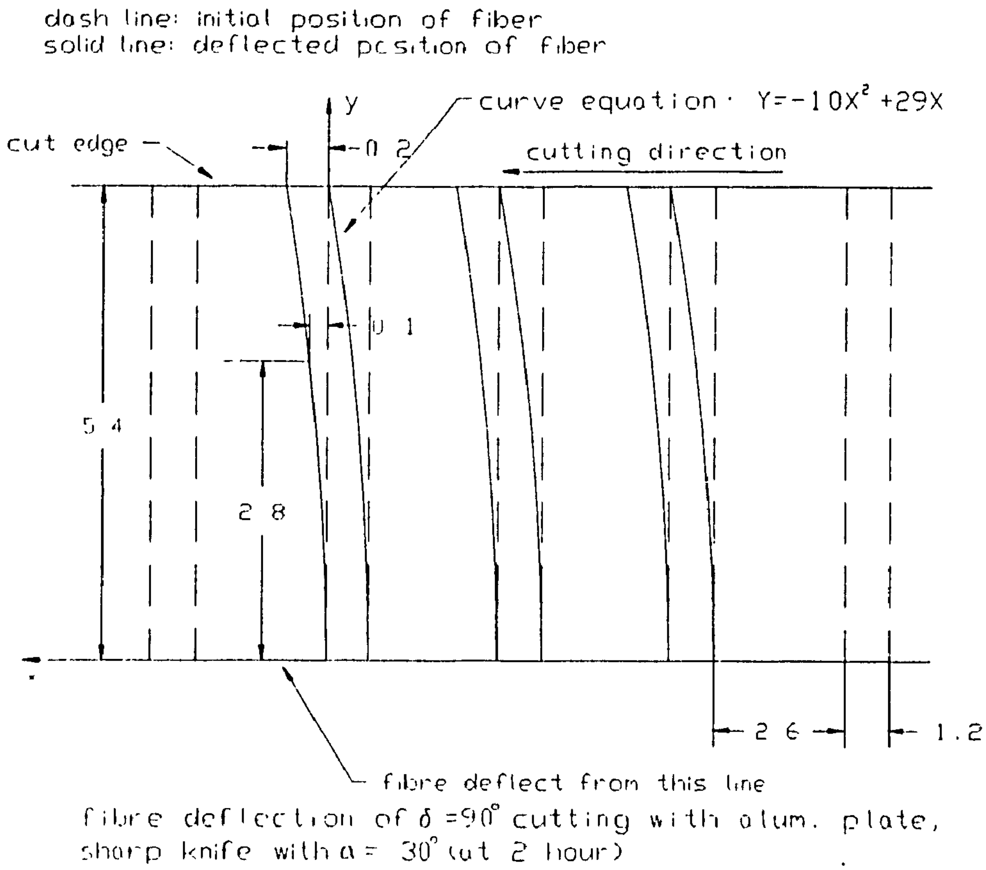

Figure 3.33 Fibre deflection at 2 hour for δ=90° cutting of woven prepreg (condition: sharp knife with $\alpha = 30°$, aluminum plate backing)

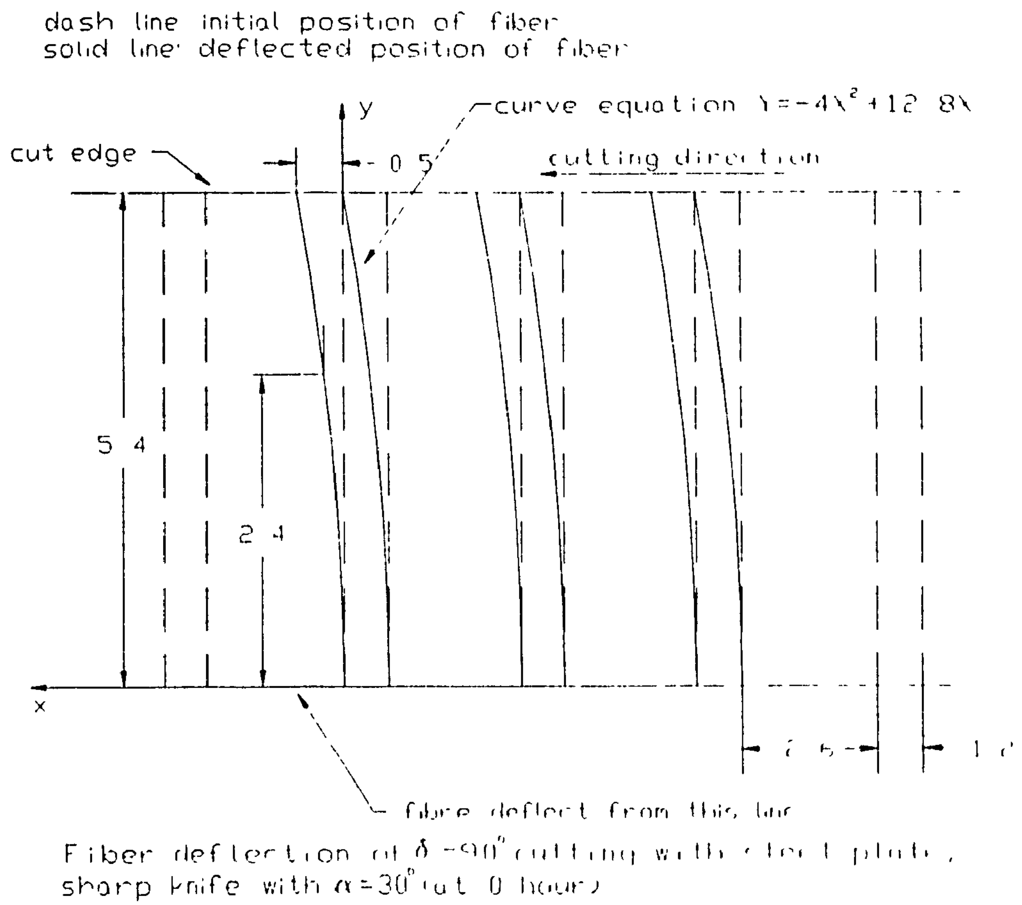

Figure 3.34 Fibre deflection at 0 hour for δ=90° cutting of woven prepreg

(condition: sharp knife with α = 30°, steel plate backing)

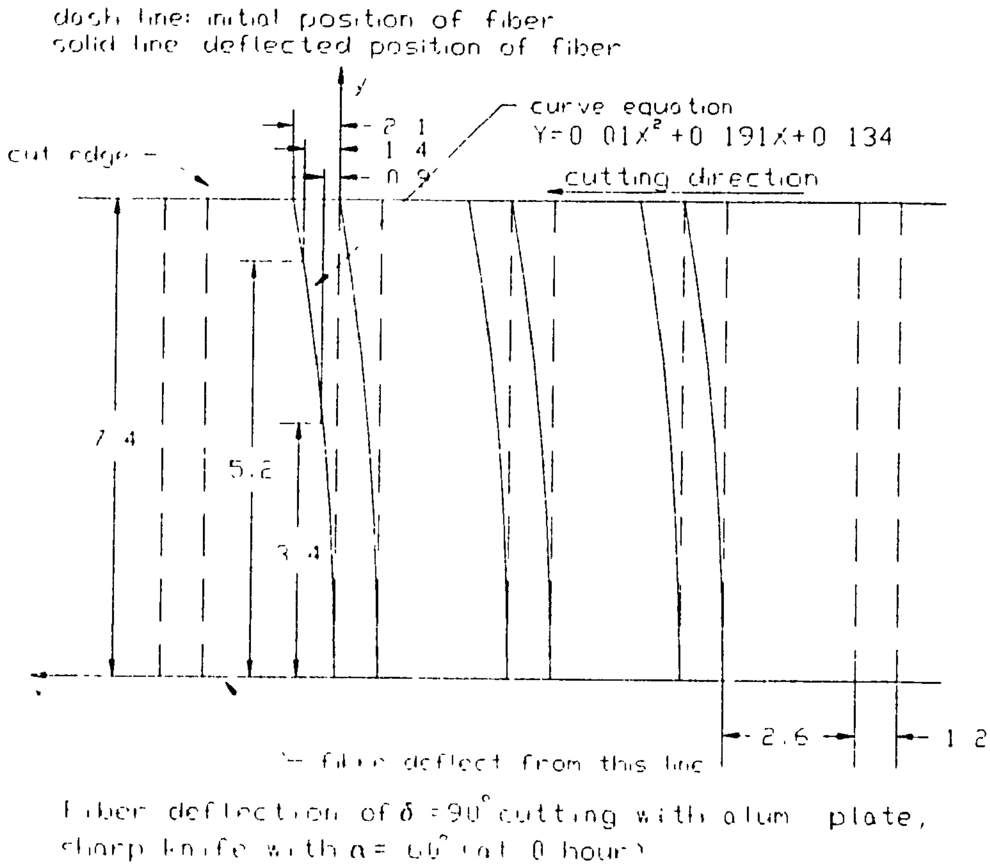

Figure 3.35 Fibre deflection at 0 hour for δ=90° cutting of woven prepreg

(condition: sharp knife with α = 60°, aluminium plate backing)

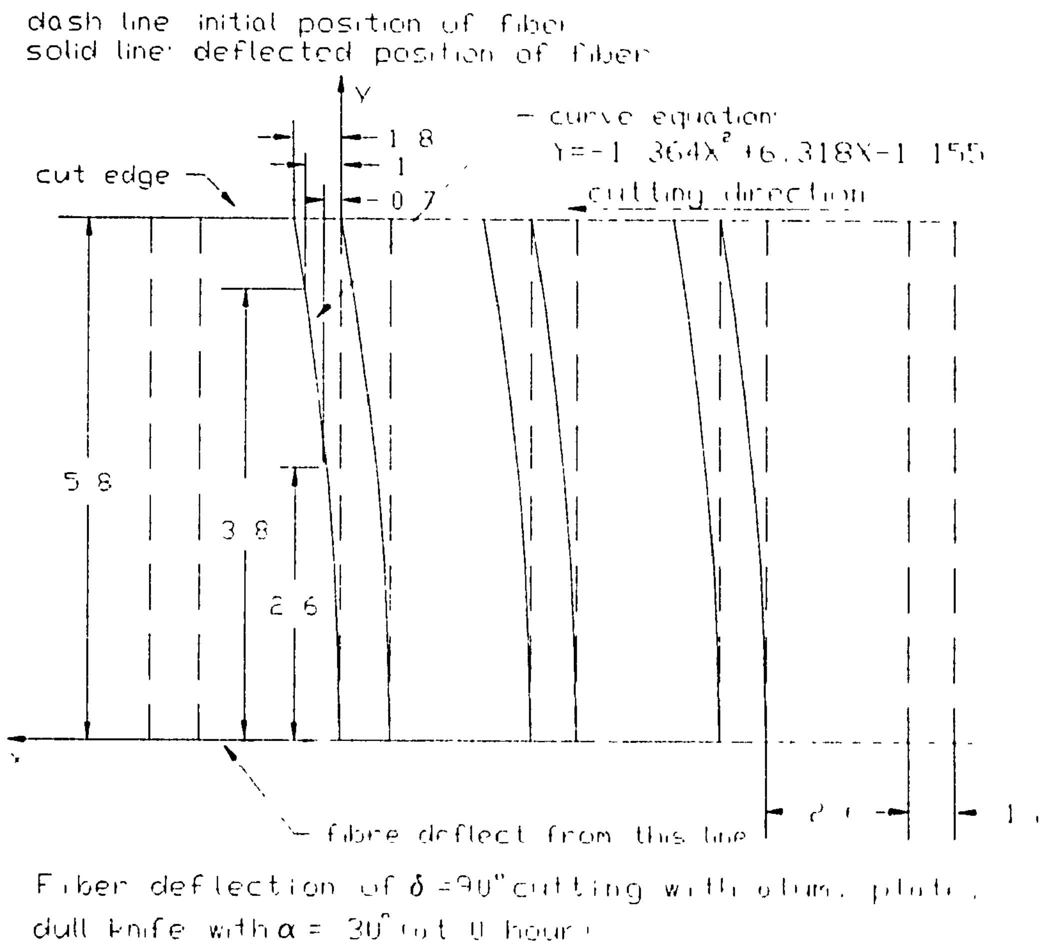

Figure 3.36 Fibre deflection at 0 hour for δ=90° cutting of woven prepreg (condition:dull knife with $\alpha = 30°$, aluminum plate backing)

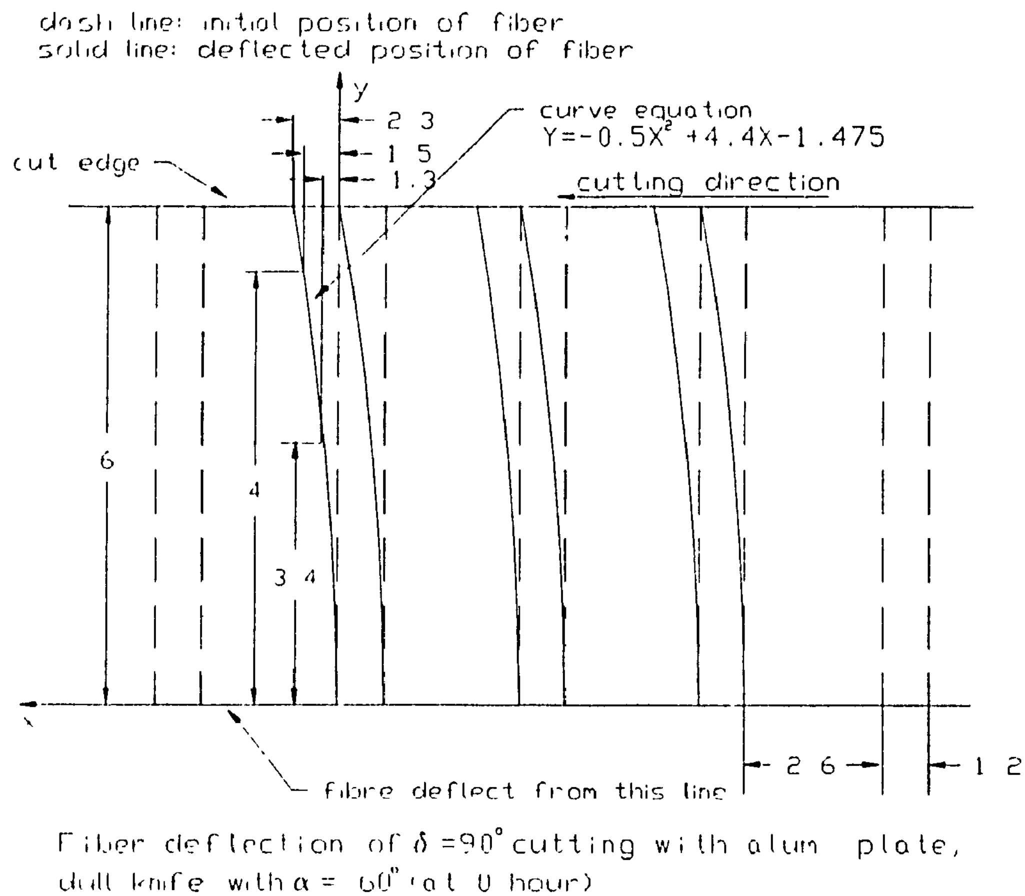

Figure 3.37 Fibre deflection at 0 hour for δ=90° cutting of woven prepreg (condition: dull knife with α = 60°, aluminum plate backing)

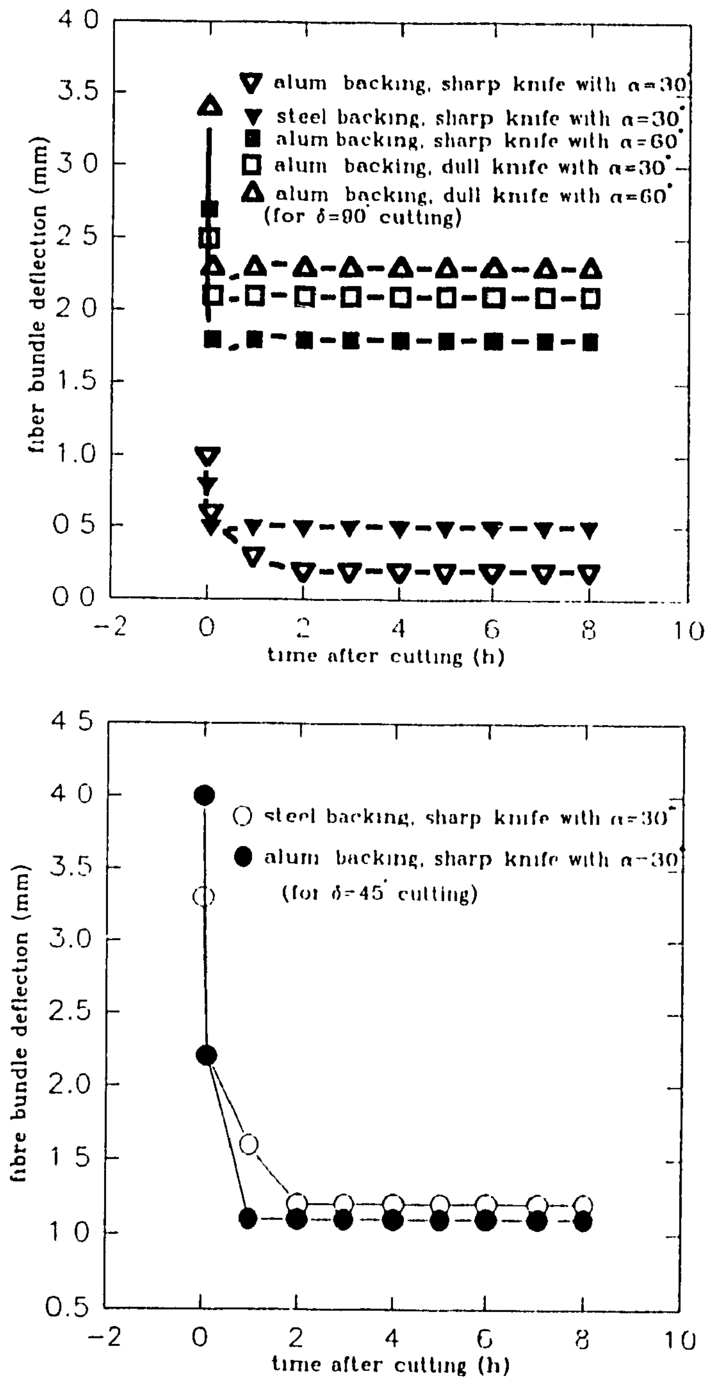

Figure 3.38 Time dependent behaviour of fibre deflection for woven prepreg cutting

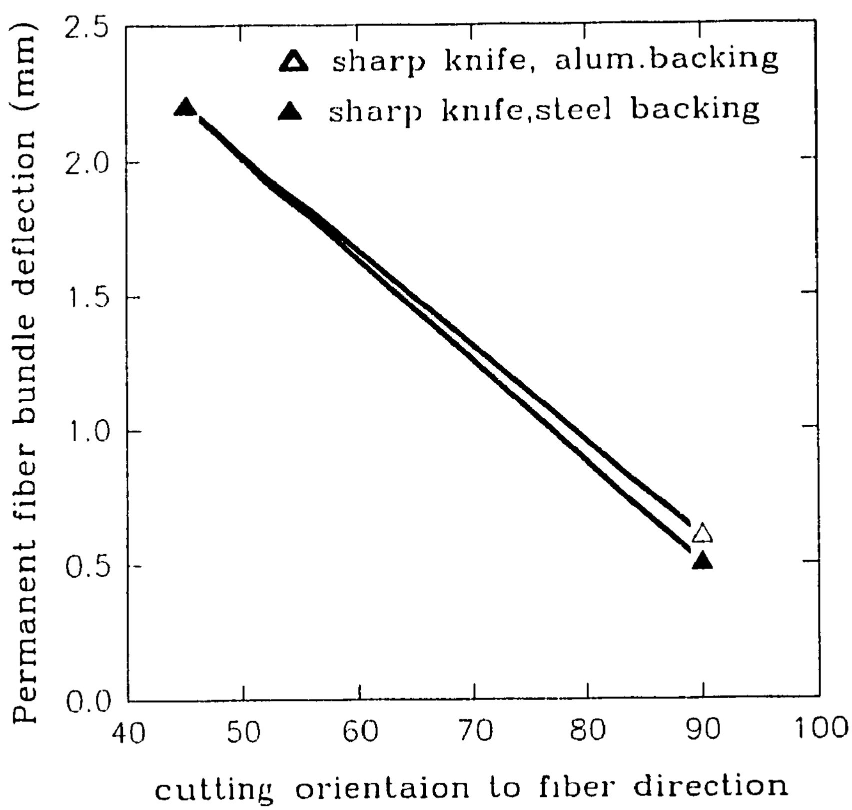

Figure 3.39 Effect of cutting orientation to fibre direction on fibre deflection for woven prepreg cutting

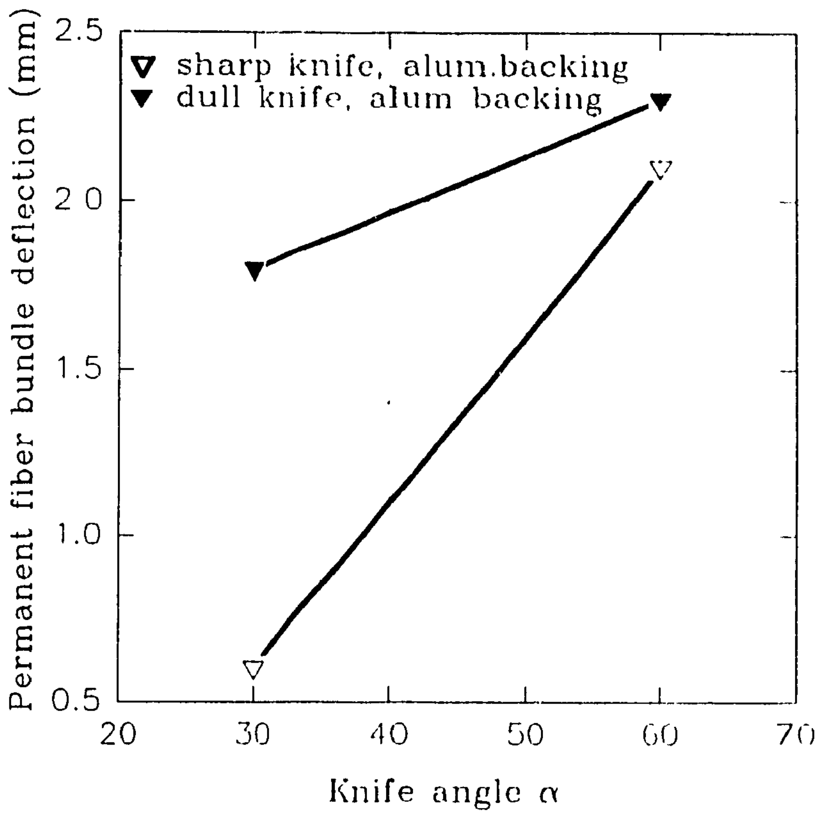

Figure 3.40 Effect of primary knife angle α on fibre deflection for woven prepreg cutting

3.4 Discussion on fibre deflection

Experimental observations show that fibre deflection exists during cutting as well as after cutting. Squeezing occurs under a certain of conditions. Figure 3.41 shows a schematic model for prepreg cutting. Based on this model, the cutting mechanism can be proposed as follows.

Prepreg cutting is an extremely complex process where the knife periodically engages regions of different mechanical properties. The relative contributions from the various processes are functions of the size, orientation and density of the fibres as well as the mechanical properties of the fibre and matrix.

During the prepreg cutting, the knife acts on the prepreg. The fibres of prepreg under the knife are pulled, deflected elastically by the cutting force and sheared and compressed as the knife moves forward. When the knife cuts the fibre, the subsequent uncut fibre and resin act as elastic foundation. After the fibres break, the resin of prepreg under the knife is ploughed and deformed due to its viscoelastic property. When the resultant strain proceeds beyond the break value of fibre, the maximum fibre deflection occurs and the fibres fracture. After the fibres fracture, both fibre and resin recoil due to the viscoelasticity of uncured resin. Moreover, the fibres can not go back to its initial orientation due to its plastic behaviour and the fibres are permanently deflected.

On the other hand, squeezing occurs during the prepreg cutting. As the knife cuts forward, the fibres of prepreg are pulled and deformed elastically by the cutting force. If the resultant strain under the knife goes beyond yield strain between fibre and resin before fibres fracture, squeezing occurs. Shearing and compressive action of knife will reduce the resultant strain of fibre and the chance of squeezing. The bending of fibre due to knife movement will promote it.

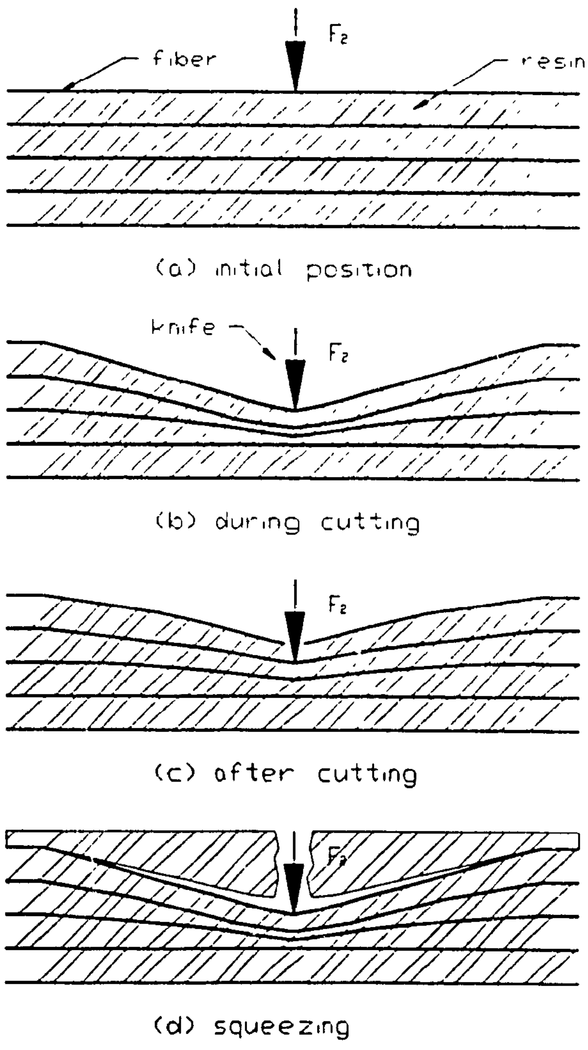

Figure 3.41 Schematic model of prepreg cutting

In order to analyze the relation between fibre deflection and cutting force, the cutting of prepreg can be simplified as a beam on elastic foundation shown in Figure 2.7.

It is difficult to observe what is really happen at the contact point between knife and fiber bundle. Therefore, the following derivation concerning the fiber deflection is an estimate. The fibre bundle concerned and resin and fibres ahead of it can be taken as a beam and the foundation respectively. The cutting force acts on the fibre bundle as a concentrated load. During the cutting, the knife cuts and pulls the fibre bundle and the subsequent fibre and resin impedes the fibre movement. Assume the knife acts on one fibre bundle. The remaining uncut fibre and resin act as elastic foundation whose elastic modulus can be calculated using rule-of-mixtures. At this time, for an unloaded portion the only force on the beam is the continuously distributed reaction from the foundation, i.e., subsequent fibre and resin. Based on the above simplification, the fibre deflection and bending moment can be estimated using the following equations [34]:

$$y=\frac{F_2}{8\zeta^3 EI_z}\phi=\frac{F_2\zeta}{2k}\phi \tag{3.1}$$

$$\zeta=\sqrt[4]{\frac{k}{4EI_z}} \tag{3.2}$$

$$\phi=e^{-\zeta x}(\cos\zeta x+\sin\zeta x) \tag{3.3}$$

where

k = elastic modulus of foundation;

F_2 = force along the cutting direction;

EI_z = flexural rigidity of fibre bundles.

In Figure 3.42, the function ϕ is shown graphically.

In equation (3.1), E is elastic modulus of fibre bundle, which is available in [39]. I_z is the moment of inertia of fibre bundle. For the current case, the fibre bundle of unidirectional prepreg is round filament whose diameter was measured to be 0.04 mm. The fibre bundle of woven prepreg is a prism whose width and thickness are 1.2 mm x 0.5 mm. The elastic modulus of foundation can be calculated using rule-of-mixture. Assume the fibre and matrix deform elastically, equation

$$E_c=E_fV_f+E_mV_m \tag{3.4}$$

can be used to calculate the modulus of the prepreg.

Where

E_c=elastic modulus of foundation;

E_f=modulus of fibre;

V_f=volume fraction of fibre;

E_m=modulus of resin;

V_m=volume fraction of resin.

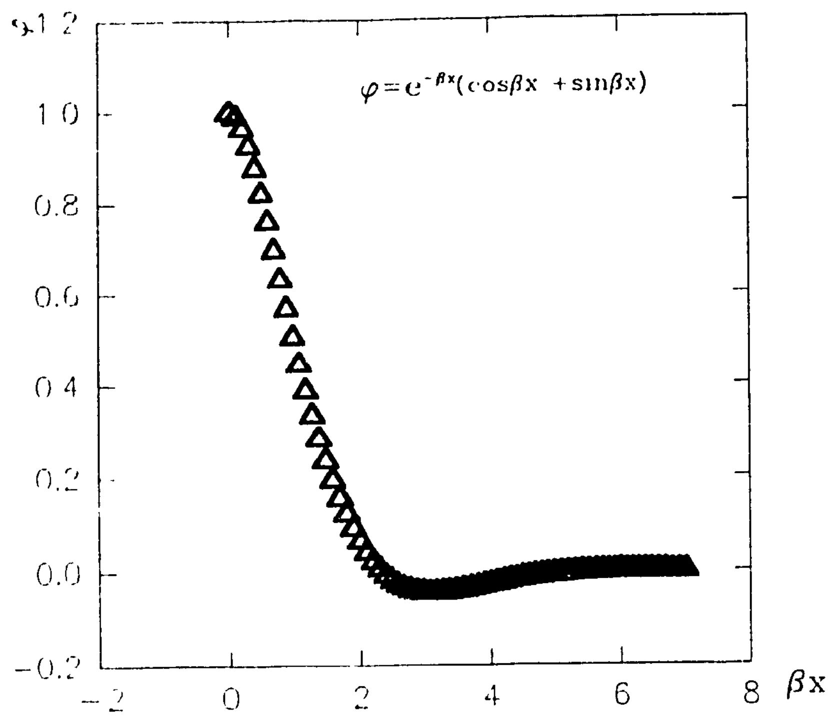

Figure 3.42 Function ϕ of βx

From equation (3.1), it is found that fibre deflection is a function of cutting force, elastic modulus of foundation and flexural rigidity of fibre bundle. The fibre deflection is directly proportional to cutting force F_2. Because the ultimate strength of fibre is fixed, if the shear stress and normal stress caused by cutting force F_1 is large and knife is sharp, the tensile stress due to bending caused by F_2 will be reduced so that the fibre deflection will be reduced and squeezing will be avoided. If elastic modulus of foundation increases, the fibre deflection will decrease.

From equation (3.1), it is also found that the elastic modulus of foundation plays a major

From equation (3.1), it is also found that the elastic modulus of foundation plays a major role in fibre deflection because it is inversely proportional to fibre deflection. The flexural rigidity EI_z of fibre bundle plays less role than elastic modulus of foundation because EI_z is fourth root of ζ which is directly proportional to fibre deflection.

Compared the fibre deflection of woven prepreg with unidirectional prepreg, it is found that the fibre deflection of woven prepreg is approximately more than 2 times as large as unidirectional prepreg. Woven prepreg has loose structure, the distance between two fibre bundles is 2.6 mm and the width of fibre bundle is 1.2 mm. However, unidirectional prepreg has compact structure, the distance between two fibre bundle is 0.05 mm and the diameter of fibre bundle is 0.04 mm. Therefore, the elastic modulus of foundation of woven prepreg is small compared with unidirectional prepreg so that the fibre deflection of woven prepreg is much larger than unidirectional prepreg.

3.5 Effect of Cutting Parameters on Strength of Cross-Ply Laminate Made of Unidirectional Prepreg Using Taguchi Method

3.5.1 Introduction

The fibre deflection exists in cut edge of prepreg after cutting. This fact may have influence on the strength of laminate and its edge delamination. Better understanding on this point is helpful. In the present study, Taguchi method was utilized to estimate the contribution of individual process parameters such as knife sharpness, backing plate, and primary knife angle α on the strength of laminate.

Taguchi method [31] is a statistical method which has been used widely in industry. The technique of Taguchi Method is done in six major steps:

1. Brain storm to identify the quality characteristics and factors important to the process.
2. Designing of the experiment.
3. Conducting experiments on specified conditions.
4. Analyzing the results using scientific methods to get optimum conditions.
5. Determining the critical factors by knowing percentage contribution of individual factors.
6. Run a confirmation test.

The Taguchi Method has advantages over the conventional design of experiment approach. The technique of defining and investigating all possible conditions in an experiment involving multiple factors is known as the design of experiments. For a full factorial design the number of possible designs N is

$$N=L^{m} \tag{3.5}$$

where

L = Number of levels for each factor

m = Number of factors

Thus, if the qualities of a given product depend on three factors A, B, and C and each factor is to be tested at 3 levels, then the equation above indicates 3^3 (27) possible design configurations. It means that the experimenter has to conduct 27 tests to understand the process. As the number of factors or number of levels increases, total number of tests also increases. For example if an engineer wants to determine the effect of seven factors at two levels, then total number of experiments becomes 2^7 (128).

Technique such as fractional factorial experiments is used to simplify the experiment. Fractional factorial experiment investigates only a fraction of all the possible combinations. This approach saves considerable time and money but requires rigorous mathematical treatment, both in the design of the experiment and in the analysis of fractional factorial experiments. Therefore, there is a need for developing a systematic approach to determine the effect of the process. Each experimenter may design a different set of fractional factorial experiments. Therefore, there is a need for developing a systematic approach to determine the effect of process parameters on the quality of end product and also to investigate which process parameters are required to be controlled to get minimum variation in the results. Taguchi made a contribution to the science of the design of experiments. He simplified and standardized the fractional factorial designs using a special set of orthogonal arrays. According to Taguchi's experimental design, only 8 experiments instead of 128 experiments for seven factors at two levels are required to get enough information about the process [31],[32].

For manufacturing process where a large number of factors influence the final outcome, Taguchi approach can be utilized to arrive at the best parameters for the optimum design configuration with the least number of analytical investigations. Therefore Taguchi method has big potential in the manufacturing area.

3.5.2 Experimental

16 laminate coupons (203.2 mm by 25.4 mm) were made from 8 ply unidirectional prepreg with stacking sequence $[\ 0,0,90,90\ ]_s$. All of them were produced by hand lay-up. A layer of polyester bleeder material supplied from Air-Tech International was placed on top of the laminate to absorb the resin. A perforated sheet was placed on top of the bleeder to give the air an escape path when vacuum is applied. The assembly was covered with a wrighton nylon film and sealed. Vacuum was drawn inside vacuum bag and the whole assembly was placed in an autoclave.

Cure cycle based on the recommended cure cycle by the manufacturer for unidirectional prepreg was applied. A pressure of 0.447 MPa (65 psi) was applied inside autoclave, with vacuum drawn on the charge. The temperature was raised to 115°C. The laminate was then soaked for 15 minutes at this temperature. The temperature was then raised to 140°C and the laminate soaked at this temperature for 60 minutes. The charge was allowed to cool to ambient temperature overnight before removal. The strength of cured laminates was measured using an MTS machine to evaluate the effect of fibre deflection on the strength of laminate. The experimental set up for measuring the strength of laminate is shown in Figure 3.43. The camera and VCR were also used to monitor the edge effect of laminate during the test.

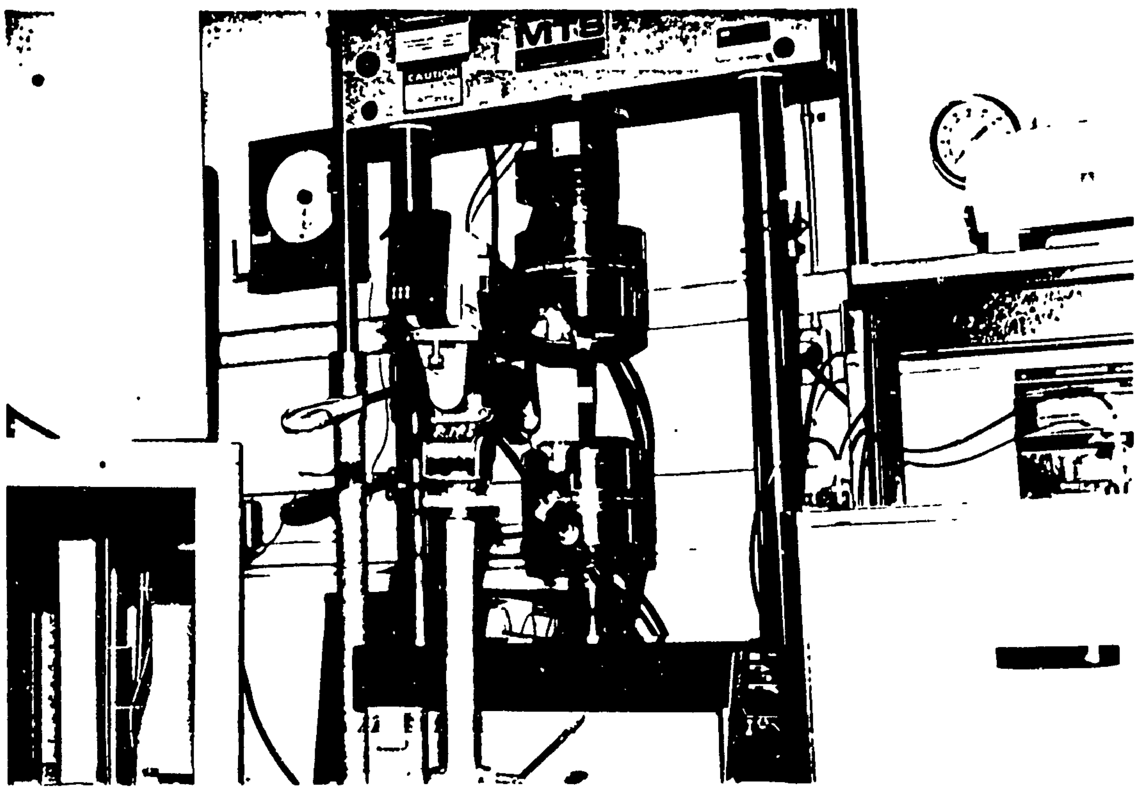

Figure 3.43 Experimental setup for measuring the strength of laminate

The tests were designed using Taguchi method to evaluate the effect of different parameters such as backing for cutting, primary knife angle α as shown in Figure 2.2 and knife sharpness on the strength of laminate made from cut prepreg and its delamination behaviour.

3.5.3 Implementation of Strength Evaluation Using Taguchi method

Following Taguchi method, the experiments on the prepreg cutting were conducted by the following procedure.

1. Designing the experiment:

Experimental design involves defining all possible conditions in an experiment including multiple factors. An experimental design must satisfy two objectives. In the first, a number of trials are calculated and in the second, conditions for each trial is specified. Taguchi developed several sets of orthogonal arrays (OAs) for designing experiments with various factors and levels. In the present case, three factors at two levels are studied as listed in table 3.1. Two levels are selected when it is compatible with knife sharpness.

For the present case, an L_4 orthogonal array (OA) as shown in table 3.2 would be suitable for experimental design. There are four independent conditions in an L_4. These conditions are described by the numbers in the row. For clarity, experimental conditions

Factors	level 1	level 2
backing of cutting (A)	aluminum plate	steel plate
primary knife angle α (B)	30^o	60^o
knife sharpness (C)	sharp	blunt

Table 3.1 Factors and their levels for unidirectional prepreg cutting

Trials	A	B	C	Y: laminate strength (MPa)				
				Y_1	Y_2	Y_3	Y_4	Y_{av}
1	1	1	1	777	949	828	720	819
2	1	2	2	751	853	928	681	803
3	2	1	2	783	628	923	705	760
4	2	2	1	815	754	781	895	811

Table 3.2 An experimental layout using L_4 array and strength of cross-ply laminate

of table 3.2 can be explained as follows:

Experiment No. 1: aluminum plate (A_1), knife with $\alpha = 30^o$ (B_1), sharp knife (C_1)

Experiment No. 2: aluminum plate (A_1), knife with $\alpha = 60^o$(B_2), blunt knife (C_2)

Experiment No. 3: steel plate (A_2), knife with $\alpha = 30^o$ (B_1), blunt knife (C_2)

Experiment No. 4: steel plate (A_2), knife with $\alpha = 60^o$ (B_2), sharp knife (C_1)

It is recommended that the trial conditions (the individual combinations in a designed experiment) should be performed randomly in order to avoid the influence of experimental set up. For the present case, four repeated experiments at each of the above conditions is performed to see the main effects of individual processing parameters.

2. Analysis of the Results:

As previously described, the laminate coupons were manufactured and the laminate strength, in terms of a quality characteristic, Y, were measured as shown below:

Y_{11} = 777 MPa, Y_{12}= 949 MPa, Y_{13} = 828 MPa, Y_{14} = 720 MPa;

Y_{21} = 751 MPa, Y_{22}= 853 MPa, Y_{23} = 928 MPa, Y_{24} = 681 MPa;

Y_{31} = 783 MPa, Y_{32}= 628 MPa, Y_{33} = 923 MPa, Y_{34} = 705 MPa;

Y_{41} = 815 MPa, Y_{42}= 754 MPa, Y_{43} = 781 MPa, Y_{44} = 895 MPa.

These results are recorded in the most right columns of the OA (Table 3.2.). Since there were four repeated tests for each condition, the results are recorded in four columns. The average of these results are as follows:

Y_{1av} = 819 MPa, Y_{2av} = 803 MPa, Y_{3av} = 760 MPa, Y_{4av} = 811 MPa.

Where $Y_{1av}=(Y_{11}+Y_{12}+Y_{13}+Y_{14})/4;$

$Y_{2av}=(Y_{21}+Y_{22}+Y_{23}+Y_{24})/4;$

$Y_{3av}=(Y_{31}+Y_{32}+Y_{33}+Y_{34})/4;$

$Y_{4av}=(Y_{41}+Y_{42}+Y_{43}+Y_{44})/4.$

The analysis of the experimental trial results was carried out using ANOVA (Analysis of Variance) technique. An initial ANOVA table was constructed. Based on concepts and equations mentioned in APPENDIX A, ANOVA (Analysis of Variance) is calculated as follows:

Total Number of Experiments:

$$n = 4 \times 4 = 16$$

Total of All Results:

$$T = 777+949+828+720+751+853+928+681$$
$$+783+628+923+705+815+754+781+895 = 12771$$

Correction Factor:

$$C.F. = T^2/n = 12771^2/16 = 1.019x10^7$$

Total Sum of Squares:

$$S_T = (777^2 + 949^2 + 828^2 + 720^2 + 751^2 + 853^2 + 928^2 + 681^2$$
$$+ 783^2 + 628^2 + 923^2 + 705^2 + 815^2 + 754^2 + 781^2 + 895^2) - C.F.$$
$$= 1.032x10^7 - 1.019x10^7 = 131370$$

Sum of Results:

To calculate the sum of results of the factor A at level 1, i.e., for A_1 , add results for trials including factor A_1 . For A_1 , we look in the column for A and find that level 1 occurs in experiment numbers 1 and 2. The effect of A_1 , is therefore calculated by adding the results, Y, of these four trials as follows:

$$A_1 = (777+949+828+720+751+853+928+681) = 6487$$

The effects of other factors are computed in a similar manner.

$$A_2 = (783+628+923+705+815+754+781+895) = 6284$$
$$B_1 = (777+949+828+720+783+628+923+705) = 6313$$

B_2 = (751+853+928+681+815+754+781+895) = 6458

C_1 = (777+949+828+720 +815+754+781+895) = 6519

C_2 = (751+853+928+681+783+628+923+705) = 6252

Factor Sum of Squares:

In the case of 2 level factors, the sum of squares can be computed using the following formulas:

$$S_A = (A_1 - A_2)^2 / (N_{A1} + N_{A2})$$

$$= (6487 - 6284)^2 / (8 + 8) = 2575.56$$

$$S_B = (B_1 - B_2)^2 / (N_{B1} + N_{B2})$$

$$= (6313 - 6458)^2 / (8 + 8) = 1314.06$$

$$S_C = (C_1 - C_2)^2 / (N_{C1} + N_{C2})$$

$$= (6519 - 6252)^2 / (8 + 8) = 4455.56$$

$$S_e = S_T - (S_A + S_B + S_C)$$

$$= 131370 - (2575.56+1314.06+4455.56) = 123034.8$$

where

N_{A1} = Total number of experiments in which factor A_1 is present

N_{B1} = Total number of experiments in which factor B_1 is present

N_{C1} = Total number of experiments in which factor C_1 is present

Total and Factor Degrees of Freedom (DOF):

DOF total = Number of test runs minus 1

$f_T = n - 1 = 16 - 1 = 15$

DOF of each factor is 1 less than the number of levels:

f_A = (Number of levels of factor A) - 1

$= 2 - 1 = 1$

f_B = (Number of levels of factor B) - 1

$= 2 - 1 = 1$

f_C = (Number of levels of factor C) - 1

$= 2 - 1 = 1$

DOF of the error term:

$f_e = f_T - (f_A + f_B + f_C)$

$= 15 - (1 + 1 + 1) = 12$

Mean Square (Variance):

$V_A = S_A/f_A \quad = 2575.56 / 1 = 2575.56$

$V_B = S_B/f_B \quad = 1314.06 / 1 = 1314.06$

$V_C = S_C/f_C \quad = 4455.56 / 1 = 4455.56$

$V_e = S_e/f_e \quad = \; 10252.07 \,/\, 12 = 10252.07$

Percentage Contribution:

$P_A = S_A/S_T \quad = 2575.56/131370 = 1.96\ \%$

$P_B = S_B/S_T \quad = 1314.06/131370 = 1\ \%$

$P_C = S_C/S_T \quad = 4455.56/131370 = 3.39\%$

$P_e = S_e/S_T \quad = 10252.07/131370 = 93.65\ \%$

F-ratio:

$F_A=V_A/V_e=2575.13/10252.07=0.25$

$F_B=V_B/V_e=1314.13/10252.07=0.13$

$F_C=V_C/V_e=4455.56/10252.07=0.44$

The results of the analysis of variance are summarized in Table 3.3.

From the F table in Taguchi method [31], find the F value at

n_1= DOF of factors =1;

n_2= DOF of error = 12.

at a confidence level (say the 90% confidence level)

F=3.177 (See appendix Table A-1)

Column	Factors	f	S	V	P	F
1	Factor A	1	2575	2575	1.96 %	0.25
2	Factor B	1	1314	1314	1 %	0.13
3	Factor C	1	4456	4456	3.39 %	0.435
All other/error		12	123035	10252	93.65 %	
Total		15			100 %	

Table 3.3 ANOVA Table for strength evaluation of laminates made from unidirectional prepreg

The value of the F-ratio for each of these parameters was smaller than that corresponding to 90% confidence limits so that the parameters such as backing for cutting, primary knife angle α and knife sharpness do not significantly affect the mean value of the process.

The reason for this is that the fibre deflection along the cut edge of prepreg due to cutting is very small. In Figure 3.10 to Figure 3.13, it is shown that its maximum is only 0.267 mm. Moreover, no edge delamination of laminate was found during the test. Therefore, fibre deflection due to cutting has no significant influence on the quality of laminate, i.e., both strength and edge delamination of laminate.

3.5.4 Theoretical calculation of cross-ply laminate strength

In order to compare the real strength of laminate made of cut prepreg with the theoretical value, laminate theory was also used to obtain the theoretical strength of laminate. This laminate is cross-ply laminate with stacking sequence $[0,0,90,90]_s$. Material properties of NCT-301 prepreg are given in table 3.4.

Longitudinal Young's modulus	Ex	113.5 GPa
Transverse Young's modulus	Ey	7.985 GPa
Poisson's ratio	υ	0.0234
shear modulus	Es	2.983 GPa
longitudinal tensile strength	X	1621 MPa
longitudinal compressive strength	X'	1621 MPa
transverse tensile strength	Y	48.28 MPa
transverse compressive strength	Y'	48.28 MPa
shear strength	S	33.3 MPa

Table 3.4 Material properties of NCT-301 prepreg

The in-plane strength of laminate is determined by examining the strength ratios of each ply orientation subjected to a given state of stress resultants as in S.W. Tsai [35].

$$[H_{kf}^{(\theta)} N_k N_f] R_{(\theta)}^2 + [H_j^{(\theta)} N_j] R_{(\theta)} - 1 = 0 \tag{3.4}$$

where

$$H_{kf}^{(\theta)} = G_{ij}^{(\theta)} a_{ik} a_{jf}$$

$$H_j^{(\theta)} = G_i^{(\theta)} a_{ij}$$

a_{ij}	In-plane compliance of laminate
G_{ij} ,G_i	Strength parameters in strain space
$H_{ij}^{(\theta)}$, $H_i^{(\theta)}$	Strength parameters of the θ - degree ply in a laminate
N_i	Stress resultant, i = 1,2,6

R(θ) = strength ratio of the θ ply orientation

a computer code was developed to calculate the strength of laminate. Finally, the tensile strength of cross-ply laminate made of NCT-301 prepreg is **888 MPa**.

3.5.5 Conclusion

The results show that the contribution of knife sharpness, backing plate and primary knife angle α to the development of laminate strength is very small. Variation in such factors during the cutting would not significantly affect the quality of strength. However, all other/error factors make great contribution to the strength of laminate. Furthermore, the theoretical strength of cross - ply laminate was calculated using laminate theory. The tensile strength is 888 MPa. In comparison with values in table 3.2, it is found that the average strength in each row is almost same as the theoretical one. In addition, in the experiment, the video camera and TV monitor were utilized to monitor the edge effect of laminate made from cut prepreg. After a few minutes when the test began, the laminate broke sharply. No edge delamination of laminate was observed. All of these indicate that the fibre deflection in unidirectional prepreg cutting has no significant effect on the quality of laminate, i.e., both strength and delamination of laminate. It is believed that the curing process using autoclave has influence on the strength of laminate. In order to increase the strength of laminate made of cut prepreg, it is important to pay attention to curing process using autoclave.

3.6 Effect of Cutting Parameters on Laminate made of Woven Prepreg Using Taguchi Method

The fibre deflection due to cutting also exists in cut edge of woven prepreg after cutting. In order to understand whether or not it has influence on the strength of laminate and its delamination, Taguchi method was utilized to estimate the contribution of individual process parameters such as knife sharpness, backing plate and primary knife angle α to it.

3.6.1 Experimental

16 laminate coupons (203.2 mm by 25.4 mm) which were stacked ply by ply in the same way were made from 8 ply 4 hardness satin woven prepreg. All of them were produced by hand lay-up. The vacuum bag was made using the same way as in section 3.4.2.

Cure cycle based on the recommended cure cycle by the manufacturer for woven prepreg was applied. A pressure of 0.584 MPa (85 psi) was applied inside autoclave. The MTS machine was used to measure the strength of laminate. The experimental set up for measuring the strength of laminate is shown in Figure 3.4 . The camera and VCR were used to monitor the edge effect of laminate during the test.

The tests were designed using Taguchi method to evaluate the effect of different parameters such as backing for cutting, primary knife angle α as shown in Figure 2.2 and knife sharpness on the strength of laminate made from cut prepreg and its delamination behaviour.

3.6.2 Implementation of Strength Evaluation using Taguchi Method

Following Taguchi method, the experiments on the prepreg cutting were conducted by the following procedure.

1. Designing the experiment:

Experimental design involves defining all possible conditions in an experiment including multiple factors. An experimental design must satisfy two objectives. In the first, a number of trials are calculated and in the second, conditions for each trial is specified. Taguchi developed several sets of orthogonal arrays (OAs) for designing experiments with various factors and levels. In the present case, three factors at two levels are studied as listed in table 3.5. Two levels are selected when it is compatible with knife sharpness.

Factors	level 1	level 2
backing plate (A)	aluminum plate	steel plate
primary knife angle α (B)	30°	60°
knife sharpness (C)	sharp	blunt

Table 3.5 Factors and their levels for woven prepreg cutting

For the present case, an L_4 orthogonal array (OA) as shown in table 3.6 would be suitable for experimental design. There are four independent conditions in an L_4. These conditions are described by the numbers in the row. For clarity, experimental conditions of table 3.6 can be explained as follows:

Experiment No. 1: aluminum plate (A_1), knife with $\alpha = 30^o$ (B_1), sharp knife (C_1)

Experiment No. 2: aluminum plate (A_1), knife with $\alpha = 60^o$(B_2), blunt knife (C_2)

Experiment No. 3: steel plate (A_2), knife with $\alpha = 30^o$ (B_1), blunt knife (C_2)

Experiment No. 4: steel plate (A_2), knife with $\alpha = 60^o$ (B_2), sharp knife (C_1)

Trials	A	B	C	Y: laminate strength (MPa)				
				Y_1	Y_2	Y_3	Y_4	Y_{av}
1	1	1	1	1559	1831	1240	1142	1143
2	1	2	2	1413	925	1248	1291	1219
3	2	1	2	1000	1346	1189	1118	1163
4	2	2	1	1189	1216	1079	764	1062

Table 3.6 An experimental layout using L_4 array and strength of woven prepreg laminate

It is recommended that the trial conditions (the individual combinations in a designed experiment) should be performed randomly in order to avoid the influence of experimental set up. For the present case, four repeated experiments at each of the above conditions is performed to see the main effects of individual processing parameters.

2. Analysis of the Results:

As previously described, the laminate coupons were manufactured and the results of MTS test, in terms of a quality characteristic, Y, were measured as shown below:

Y_{11} = 1559 MPa, Y_{12}= 1831 MPa, Y_{13} = 1240 MPa, Y_{14} = 1142 MPa;

Y_{21} = 1413 MPa, Y_{22}= 925 MPa, Y_{23} = 1248 MPa, Y_{24} = 1291 MPa;

Y_{31} = 1000 MPa, Y_{32}= 1346 MPa, Y_{33} = 1189 MPa, Y_{34} = 1118 MPa;

Y_{41} = 1189 MPa, Y_{42}= 1216 MPa, Y_{43} = 1079 MPa, Y_{44} = 764 MPa.

These results are recorded in the most right columns of the OA (Table 3.6). Since there were four repeated tests for each condition, the results are recorded in four columns. The average of these results are as follows:

Y_{1av} = 1143 MPa, Y_{2av}=1219 MPa, Y_{3av}=1163 MPa, Y_{4av}=1062 MPa.

$$Y_{1av}= (Y_{11}+Y_{12}+Y_{13}+Y_{14})/4;$$

Y_{2av}= $(Y_{11}+Y_{12}+Y_{13}+Y_{14})/4$;

Y_{3av}= $(Y_{11}+Y_{12}+Y_{13}+Y_{14})/4$;

Y_{4av}= $(Y_{11}+Y_{12}+Y_{13}+Y_{14})/4$.

Here, the average of results was utilized to evaluate the test.

3. Computation of Average Performance:

To compute the average performance of the factor A at level 1, i.e., for A_1 , add results of trials including factor A_1 , and then divide them by the number of such trials.

For A_1 , one looks in the column for A and find that level 1 occurs in experiments numbered 1 and 2. The average effect of A_1 , is therefore calculated by adding the results, Y_{av}, of these four trials as follows:

A_{1av} = $(Y_{1av} + Y_{2av})/2 = (1143+ 1219)/2 = 1181$

The average effects of other factors are computed in a similar manner.

A_{2av} = $(Y_{3av} + Y_{4av})/2 = (1163+ 1062)/2 = 1113$

B_{1av} = $(Y_{1av} + Y_{3av})/2 = (1143+ 1163)/2 = 1153$

B_{2av} = $(Y_{2av} + Y_{4av})/2 = (1219+ 1062)/2 = 1141$

C_{1av} = $(Y_{1av} + Y_{4av})/2 = (1143+ 1062)/2 = 1103$

C_{2av} = $(Y_{2av} + Y_{3av})/2 = (1219+ 1163)/2 = 1191$

Above values are plotted in Figure 3.44 to see the main effects of individual parameters

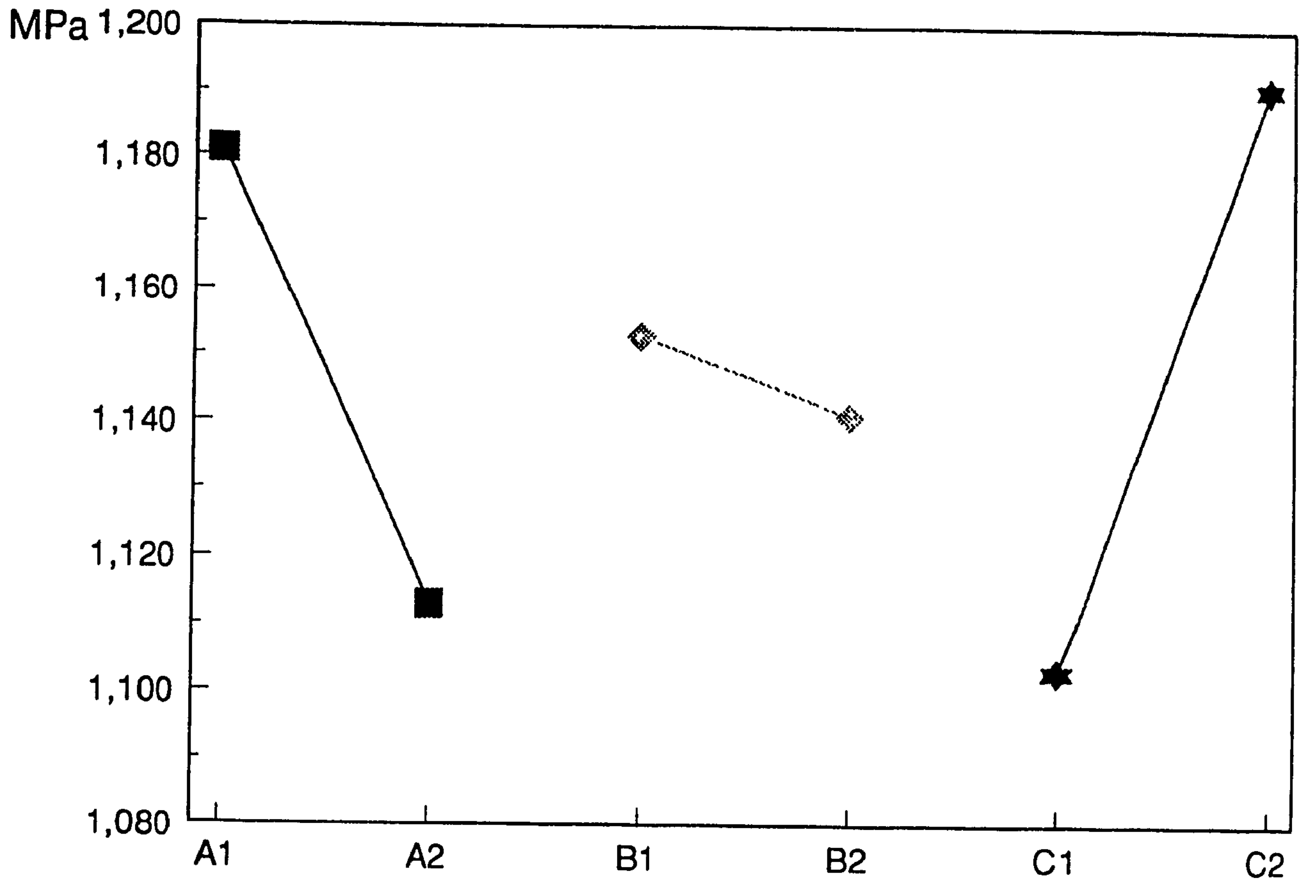

Figure 3.44 Main effect of factors on MTS test results for woven prepreg cutting

on the quality of laminate. It is clear from the figure that the increase in the stiffness of backing (from aluminum plate to steel plate) decreases the strength of laminates made of cut prepreg. The increase in primary knife angle α also decreases the strength of laminate made of cut prepreg. The reason for decrease of the strength of laminate with increase in primary knife angle α is that fibre deflection will increase with increase in primary knife angle α shown in Figure 3.40. The large fibre deflection along the cut edge of prepreg will result in the decrease of the strength of laminate. Variation of knife sharpness is found to be negligible.

4. Quality Characteristics:

For the present case, higher strength of the laminate is desired, and thus, " the bigger the better." From Figure 3.44 the $A_1B_1C_2$ will likely produce the best result.

In terms of the actual design factors, the probable optimum condition is:

A_1 i.e., aluminium plate

B_1 i.e., primary knife angle α at 30°

C_2 i.e., blunt knife.

5. Relative Contribution of Variables

Based on concepts and equations mentioned in APPENDIX A, ANOVA (Analysis of Variance) is calculated as follows:

<u>Total Number of Experiments:</u>

$n = 4 \times 4 = 16$

<u>Total of All Results:</u>

T=1559+1831+1240+1142+1413+925+1248+1291+1000+1346

+1189+1118+1189+1216+1079+764 = 19610

Correction Factor:

C.F. = $T^2/n = 19610^2/16 = 2.4x10^7$

Total Sum of Squares:

S_T=($1559^2+1831^2+1240^2+1142^2+1413^2+925^2+1248^2+1291^2+1219^2+1000^2+1346^2$

$+1189^2+1118^2+1189^2+1216^2+1079^2+764^2$) - C.F.

$= 2.5x10^7 - 2.4x10^7 = 1x10^6$

Sum of Results:

To calculate the sum of results of the factor A at level 1, i.e., for A_1 , add results for trials including factor A_1 . For A_1 , we look in the column for A and find that level 1 occurs in experiment numbers 1 and 2. The effect of A_1 , is therefore calculated by adding the results, Y, of these four trials as follows:

A_1 = (1559+1831+1240+1142+1413+925+1248+1291) = 10649

The effects of other factors are computed in a similar manner.

A_2 = (1000+1346+1189+1118+1189+1216+1079+764) = 8901

B_1 = (1559+1831+1240+1142+1000+1346+1189+1118) = 10485

B_2 = (1413+925+1248+1291+ 1189+1216+1079+764) = 9125

C_1 = (1559+1831+1240+1142+1189+1216+1079+764) = 10080

C_2 = (1413+925+1248+1291+1189+1216+1079+764) = 9530

Factor Sum of Squares:

In the case of 2 level factors, the sum of squares can be computed using the following formulas:

$$S_A = (A_1 - A_2)^2 / (N_{A1} + N_{A2})$$

$$= (10649 - 8901)^2 / (8 + 8) = 204304$$

$$S_B = (B_1 - B_2)^2 / (N_{B1} + N_{B2})$$

$$= (10485 - 9125)^2 / (8 + 8) = 115600$$

$$S_C = (C_1 - C_2)^2 / (N_{C1} + N_{C2})$$

$$= (10080 - 9530)^2 / (8 + 8) = 18906$$

$$S_e = S_T - (S_A + S_B + S_C)$$

$$= 1000000 - (204304 + 115600 + 18906) = 666863.8$$

where

N_{A1} = Total number of experiments in which factor A_1 is present

N_{B1} = Total number of experiments in which factor B_1 is present

N_{C1} = Total number of experiments in which factor C_1 is present

Total and Factor Degrees of Freedom (DOF):

DOF total = Number of test runs minus 1

$f_T = n - 1 = 16 - 1 = 15$

DOF of each factor is 1 less than the number of levels:

f_A = (Number of levels of factor A) - 1

= 2 - 1= 1

f_B = (Number of levels of factor B) - 1

= 2 - 1 = 1

f_C = (Number of levels of factor C) - 1

= 2 - 1 = 1

DOF of the error term:

$f_e = f_T - (f_A + f_B + f_C)$

= 15 - (1 + 1 + 1) = 12

Mean Square (Variance):

$V_A = S_A/f_A$ = 204304 / 1 = 204304

$V_B = S_B/f_B$ = 115600 / 1= 115600

$V_C = S_C/f_C$ = 18906 / 1 = 18906

$V_e = S_e/f_e$ = 666863.8 / 12 = 55571.98

Percentage Contribution:

$P_A = S_A/S_T$ = 204304/1000000 = 20.40 %

$P_B = S_B/S_T$ = 115600/1000000 = 11.56 %

$P_C = S_C/S_T$ = 18906/1000000 = 1.89 %

$P_e = S_e/S_T$ = 666863.8/1000000 = 66.7 %

The results of the analysis of variance are summarized in Table 3.7.

3.6.3 Conclusion

The ANOVA table shows that the backing plate significantly affects the strength of laminate made from woven prepreg. Its value of the F ratio (see appendix) was greater than that corresponding to 90% confidence limits. The results show that backing plate contributes 20.40% to the strength of the laminate and the primary knife angle α contributes 11.56% to it, therefore, both of them should be controlled properly to reduce the standard deviation. Contribution of knife sharpness in the development of strength of laminate is only 1.89%,

Column	Factors	f	s	v	F	P
1	Factor A	1	204304	204304	3.68	20.40%
2	Factor B	1	115600	115600	2.08	11.56%
3	Factor C	1	18906	18906	0.34	1.89%
All other/error		12	666863.8	55571.9		66.3%
Total		15				100%

Table 3.7 ANOVA Table for strength evaluation of laminate made from woven prepreg

therefore, variation in knife sharpness would not significantly affect the strength of laminate. This is different from unidirectional prepreg cutting. In that case, neither of these factors (cutting backing, primary knife angle α and knife sharpness) has any significant effect on the strength of coupon. In previous section 3.5.5, it is concluded that the fibre deflection in unidirectional prepreg cutting has no significant effect on the quality of laminate, i.e., both strength and delamination of laminate. Upon checking the fibre deflection of woven prepreg due to cutting, it is found that the fibre deflection of woven prepreg is more than 2 times larger than of unidirectional prepreg and the deformed area of woven prepreg is more than 2 times larger than of unidirectional prepreg. Therefore, if fibre deflection due to cutting is large enough, it has effect on the quality of laminate made from cut edge. It is also found that the contribution of error factor is 66.3%. It means that something unknown has effect on the quality of laminate made from cut prepreg. It is important to pay attention to curing process because it is well known that curing process has influence on it.

During the test, the video camera and TV monitor were utilized to monitor the edge effect of laminate. It was found that the laminate broke sharply. No edge delamination was observed. Therefore, fibre deflection due to cutting does not cause delamination of laminate made from cut edge for either unidirectional prepreg cutting or woven prepreg cutting.

CHAPTER 4

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

4.1 Conclusions

The experiments using sign cutting machine to cut composite prepreg have been done. The effects of cutting parameters of sign - cutting machine on cutting quality have been investigated. The experiments were also conducted to investigate the fibre deflection during the cutting and after cutting under the different conditions for both unidirectional prepreg and woven prepreg. The effects of the fibre deflection on the sample strength were evaluated using Taguchi method. The equations to express the curvature of fibre deflection were formulated. From the investigation, the following conclusions can be made:

1. The cover is the most important factor on cut edge quality of prepreg. Because the prepreg is the B-stage, there is almost no strength for resin. The cover can constrain and support the prepreg. Cutting force and knife (geometry & material) also have effect on cut edge quality. Cutting speed is not an important factor for cut edge quality of prepreg.

2. Fibre orientation to cutting direction δ has great influence on the edge quality. When δ is equal to 0° or in the range from 45° to 90°, the edge quality is

acceptable. When δ is in the range from 0^{o} to 45^{o}, the edge quality is not acceptable.

3. The principle material removal mechanism is material failure associated with bending-induced fracture, shearing and compressive stress. The resin of prepreg is ploughed and the reinforced fibres of prepreg crack due to bending and shearing. The appropriate cutting force will promote the edge quality.

4. There is no time dependent behaviour for unidirectional and woven prepreg cutting except for that a few cases for woven prepreg cutting have time dependent behaviour.

5. For unidirectional prepreg cutting, the fibre deflection is small so that it has no effect on the strength of coupon and factors such as backing plate, primary knife angle α and knife sharpness have no significant effect on it. For woven prepreg cutting, the fibre deflection is large enough to have effect on the strength of coupon and factors such as backing plate and primary knife angle α have significant effect on the fibre deflection. Knife sharpness is not significant factor. Fibre deflection due to cutting does not cause delamination of laminate made from cut edge for either unidirectional or woven prepreg.

It is believed that the curing process using autoclave has much influence on the strength of laminate. In order to increase the strength of laminate made of cut prepreg, it is important to pay attention to curing process using autoclave .

4.2 Suggestions for the future

In this thesis, a certain of work have been done for graphite fibre reinforced prepreg cutting. The following work is felt necessary to be done in the future:

1. Because the composite prepreg is a kind of material hard to cut due to the reinforced fibre, knife wear is a big problem. Further experiments should be conducted to find the optimum knife material to make knife sharpness last longer.

2. The good cutting quality of composite prepreg can be obtained through enough cutting force and small knife angle. Further work can be done to find suitable cutting force and knife geometry. This information is important for cutting machine builder.

3. A mathematical model using plasticity mechanics and fracture mechanics need to be developed to predict the fibre fracture.

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APPENDIX

THE CONCEPTS AND EQUATIONS FOR THE CALCULATION of ANOVA BASED ON TAGUCHI METHOD

The relative contributions of the factors are determined by comparing their variances. The technique, popularly known as the analysis of variance (ANOVA) is used for this purpose.

In an experiment designed to determine the effect of factor A on response Y, factor A is to be tested at L levels. Assume n_1 is the numbers of repetitions of each trial that includes A_1 . Similarly at level A_2 the trial is to be repeated n_2 times. The total number of trial is the sum of the number of trials at each level, i.e.,

$$n = n_1 + n_2 + \ldots\ldots + n_L \tag{A1}$$

Degrees of Freedom (DOF) is an important and useful concept that is difficult to define. It is a measure of the amount of information that can be uniquely determined from a given set of data. DOF for data concerning a factor equals one less than the number of levels. For a factor A with four levels, A_1 data can be compared with A_2, A_3 and A_4 data and not with itself. Thus a 4 level factor has 3 DOF. Similarly an L_4 OA with three columns representing 2 level factors, has 3 DOF.

The concept of DOF can be extended to the experiment. An experiment with n trial and r repetitions of each trial has n x r trial runs. The total DOF becomes

$$f_T = nxr - 1 \tag{A2}$$

Similarly, the DOF for a sum of squares term is equal to the number of terms used to compute the sum of squares and the DOF of the error term f_e is given by:

$$f_e = f_T - f_A - f_B - f_C \tag{A3}$$

Let

$$T = \sum_{i=1}^{n} (Y_i - Y_0) \tag{A4}$$

where

T = the sum of all deviations from the target value

The mean sum of squares of the deviation is:

$$\frac{T^2}{n} = \frac{[\sum_{i=1}^{n} (Y_i - Y_0)]^2}{n} \tag{A5}$$

The sum of squares is a measure of the deviation of the experimental data from the mean value of the data. Summing each squared deviation emphasizes the total deviation. Thus

$$S_T=\sum_{i=1}^{n}(Y_i-\overline{Y})^2 \tag{A6}$$

where

$\overline{Y}$ is the average value of Y_i.

Similarly the sum of squares of deviations S_T, from a target value Y_0, is given by;

$$S_T=\sum_{i=1}^{n}(Y_i-Y_o)^2-C.F. \tag{A7}*$$

Where

Y_o is the target value of Y_i .

$C.F. = T^2/n$

---

*

$$S_T=\sum_{i=1}^{n}(Y_i-Y_o)^2$$

$$=\sum_{i=1}^{n}(Y_i-\overline{Y}+\overline{Y}-Y_o)^2$$

$$=\sum_{i=1}^{n}[(Y_i-\bar{Y})^2+2(Y_i-\bar{Y})(\bar{Y}-Y_0)+(\bar{Y}-Y_o)^2]$$

$$=\sum_{i=1}^{n}(Y_i-\bar{Y})^2+\sum_{i=1}^{n}2(Y_i-\bar{Y})(\bar{Y}-Y_0)+\sum_{i=1}^{n}(\bar{Y}-Y_o)^2$$

Since

$$\sum_{i=1}^{n}(Y_i-\bar{Y})=\sum_{i=1}^{n}Y_i-\sum_{i=1}^{n}\bar{Y}=n\bar{Y}-n\bar{Y}=0$$

and

$$\sum_{i=1}^{n}(\bar{Y}-Y_0)^2=n(\bar{Y}-Y_0)^2$$

The above equation becomes,

$$S_T=\sum_{i=1}^{n}(Y_i-\bar{Y})^2=\sum_{i=1}^{n}(Y_i-Y_0)^2-n(\bar{Y}-Y_0)^2=\sum_{i=1}^{n}(Y_i-Y_0)^2-\frac{T^2}{n}$$

The sum of squares for the factor A can be calculated by:

where,

L = number of levels

$$S_A=\sum_{k=1}^{L}\frac{1}{n_k}[\sum_{i=1}^{n}(A_{ik}-Y_0)]^2-\frac{T^2}{n}$$

n_i ,n_k = number of test samples at levels A_i and A_k, respectively

T = sum total of all deviations from the target value

n = total number of observations

The T^2/n is called the correction factor, C.F.

Finally,

$$S_T=S_A+S_B+......+S_e \tag{A8}$$

Variance measures the distribution of the data about the mean of the data. Since the data is representative of only a part of all possible data, DOF rather than the number of observations is used in the calculation.

Variance = Sum of Squares / Degrees of Freedom

or $V = S_T/f$

Therefore:

$$V_T=S_T/f_T \tag{A9}$$

$$V_A = \frac{S_A}{f_A} \tag{A10}$$

$$V_e = (S_T - S_m)/f_e = \sigma^2 \tag{A11}$$

$$V_T = V_A + V_B + \ldots\ldots + V_e \tag{A12}$$

where:

V_T is total variance;

V_A is factor variance;

V_e is error variance.

The variance ratio, commonly called the F statistic, is the ratio of variance due to the effect of a factor and variance due to the error term. The ratio is used to measure the significance of the factor under investigation with respect to the variance of all the factors included in the error term. The F value obtained in the analysis is compared with a value from standard F-tables for a given statistical level of significance.

To use the tables, enter the DOF of the numerator to determine the column and the DOF of the denominator for the row. The intersection is the F value. When the computed F value is less than the value determined from the F tables at the selected level of significance, the factor does not contribute to the sum of the squares within the confidence level.

For a factor A, F value is calculated by:

$$F_A=\frac{V_A}{V_e} \tag{A13}$$

f_1 / f_2	1	2	3	4	5	6	7	8
1	39.864	49.500	53.593	55.833	57.241	58.204	58.906	59.44
2	8.526	9.000	9.162	9.243	9.293	9.326	9.349	9.367
3	5.538	5.462	5.391	5.343	5.309	5.285	5.266	5.252
4	4.545	4.325	4.191	4.107	4.051	4.010	3.979	3.955
5	4.060	3.780	3.620	3.520	3.453	3.405	3.368	3.339
6	3.776	3.463	3.289	3.181	3.108	3.055	3.015	2.893
7	3.589	3.257	3.074	2.960	2.883	2.827	2.745	2.752
8	3.458	3.113	2.924	2.806	2.727	2.668	2.624	2.859
9	3.360	3.007	2.813	2.693	2.611	2.551	2.505	2.459
10	3.285	2.925	2.728	2.605	2.522	2.461	2.414	2.377
11	3.225	2.860	2.660	2.536	2.451	2.398	2.342	2.304
12	3.177	2.807	2.606	2.480	2.394	2.331	2.283	2.245
13	3.136	2.763	2.560	2.434	2.347	2.283	2.234	2.195
14	3.102	2.727	2.522	2.395	2.306	2.243	2.193	2.154

Table A-1 F table F.10 (f_1,f_2), 90% Confidence
f_1 = No. of degrees of freedom of numerator f_2 = No. of degrees of freedom of denominator