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Forming technology for thermoset composites

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10.1 Introduction

Pre-impregnated continuous fibre reinforcement (called prepreg) is a form of reinforcement very commonly used in the manufacture of 'advanced composite' structures. Prepreg technology is strongly associated with the aircraft industry, but is also used extensively in the manufacture of sporting equipment, racing and performance cars, wind-turbine blades, and racing yachts. Although continuous fibre impregnated with thermoplastic resin, and short fibre impregnated with thermoset resins, are sometimes also called prepreg, in this chapter the term will describe continuous fibre reinforcement impregnated with a partially-cured thermosetting resin, typically epoxy.

Currently most continuous-fibre-reinforced thermoset composite parts for aircraft are formed by successive lamination and shaping of single plies of prepreg on a shaped mould surface. Only one ply is normally handled at a time, and the shaping of the ply is done at the same time as the lamination. Where the parts are made from fabric prepreg, the shaping and lamination of the single plies is almost always done by hand. This is very appropriate and efficient for small production runs, and complex components, but the hand-laminated components are less competitive for high-volume production.

To automate production of advanced (thermoset) composite parts from prepreg, the aircraft industry has progressively developed machine tools called Automated Tape Laying (ATL) and Automated Tow Placement (ATP) machines. These numerically controlled machines resemble large six-axis gantry milling machines, but incorporate a very expensive prepreg tape dispenser as the end-effector. They lay down unidirectional prepreg tape along a pre-determined numerically controlled path to create laminates of unidirectional tape prepreg which are then vacuum-bagged and cured in an autoclave.

Many carbon-epoxy parts, however, such as ribs, spars or brackets, are too small or too complex in shape to be efficiently manufactured using such machines. To bring the benefits of automation to the manufacture of some of these parts, some aerospace industry engineers have started to reorganise the layup process into two stages. A flat stack of plies, typically 1 mm to 5 mm thick, with the correct shape and layup, is first created by hand layup, by ATL machine, or by a dedicated flat laminating machine. This flat stack is then transferred to the mould tool, where it is formed (shaped) as one unit around the mould tool, before being cured in the normal way.

This chapter is thus concerned with the forming of stacks of prepreg which will subsequently be cured under heat and compaction to form a laminated thermoset composite component. The process of forming prepreg is not as widely known, or well developed, as the corresponding processes for the forming of dry reinforcement stacks (generally known as preforming) or the forming of preconsolidated thermoplastic composite laminates (often known as thermoforming). However, the process is very efficient, and is likely to become much more popular.

10.2 Practicalities of forming thermoset prepreg stacks

There are many common types of thermoset prepreg. The fibre reinforcement is normally a type of glass fibre or carbon fibre, although other fibres such as boron, aramid, basalt, quartz or even steel are sometimes used. The fibre is impregnated with a thermosetting resin mixture such as an epoxy or bismaleimide. This resin is distributed evenly through the reinforcement and usually partially cured, to prevent resin run-off and to give the prepreg the right handling qualities. The aircraft industry mostly uses carbon-epoxy prepreg designed to be cured at around 175ºC to 180ºC, and this material should be assumed for the rest of this chapter.

In most cases prepregs have been designed to be laid up by hand. (Prepreg tape may be optimised for ATL, with more accurate control of the resin amount, and lower tack. However, the author is unaware of any prepreg which has been specifically optimised for ease of forming.) The degree of cure of the resin, the resin content, and the tackiness of the resin, have been adjusted to suit a manual operator, often working with gloves, who wants to be able to handle large plies of prepreg easily, and shape it without excessive force. The operator needs the tackiness (tack) to be high enough to hold the ply in place after layup, but not so high that the ply cannot be safely removed if it is laid down incorrectly. The prepreg is normally delivered covered with two plies of 'backing paper' to keep it clean until layup. Unidirectional tape prepreg is usually from 0.1 to 0.2 mm thick: fabric prepreg thickness typically ranges from 0.2 to 0.4 mm.

Prepreg is perishable. The resin gradually stiffens, hardens, and loses its tack if exposed to the air and to room temperature. If not being used, prepreg is normally sealed and stored at −18ºC, and needs to be warmed to room temperature before use. Therefore the deformation characteristics depend on the time that the prepreg has been exposed to room temperature, otherwise known as the 'age' or 'out-time' of the prepreg. A maximum allowed 'out-life' of between 10 days and a month is typical for prepreg designed for hand layup. The forming characteristics of the prepreg can change considerably over this period.

The viscosity and tack of the epoxy resin is quite sensitive to temperature and humidity as well as age. It is also somewhat sensitive to shear history. Although process specifications allow some heating of prepreg in order to facilitate hand shaping, heating to temperatures higher than is safe for skin contact is usually not allowed during hand layup.

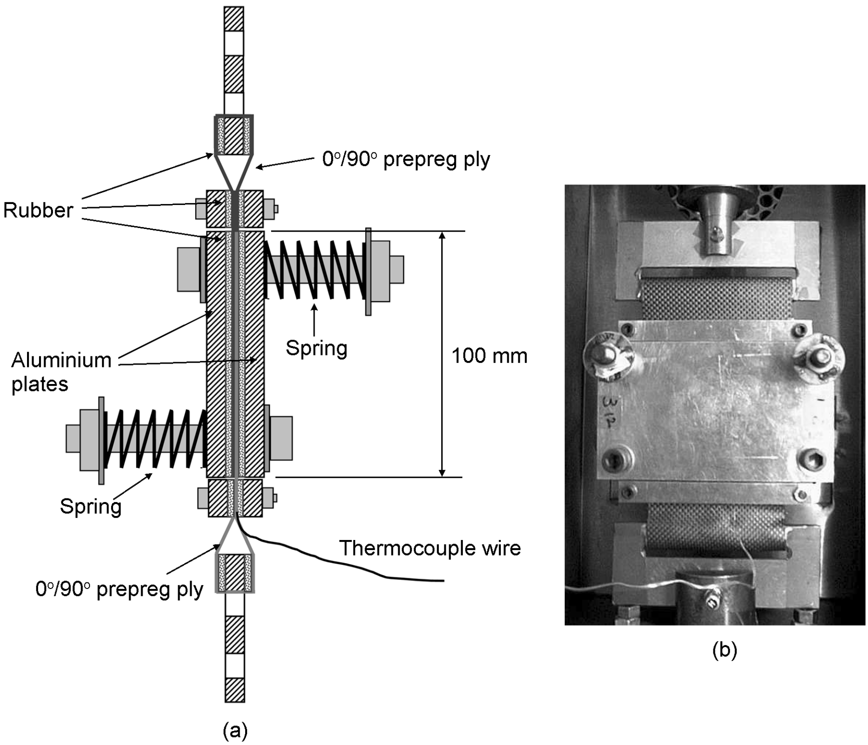
Composite laminates can be designed with quite anisotropic structures. However, in most cases, carbon-epoxy parts found in aircraft include reinforcement fibres oriented towards each of the four points of the compass: i.e. fibres oriented at 0º, 45º, 90º, and 135º (−45º) to a given reference direction. Many have a layup which is 'quasi-isotropic', with an equal number of plies in each direction. Design guidelines discourage grouping of plies with the same orientation together. This means that in parts made with fabric prepreg, most 0º/90º plies are in contact with two ±45º plies, and in parts made with tape prepreg, a 0º ply might typically be in contact with a 45º and a 135º ply. It is a normal requirement that the stack layup is symmetrical about its centre ply to avoid warping of the laminate following cure and subsequent cool down.

10.3 Deformation mechanisms in woven fabric prepreg

Woven fabric prepreg stacks have the same deformation modes as dry fabric stacks. The most important modes are interply slip and intraply shear, while out-of-plane bending of the fabric and tows, and in-plane bending of tows, are also necessary. Slippage between the tows does not occur so readily as with dry fabric. Refer to Chapter 1 for a detailed description of stack and fabric deformation mechanisms and associated characterisation techniques.

10.3.1 Interply slip

In the forming of thermoset prepreg stacks, interply slip (also known as interply shear) is the most important deformation mechanism. Interply slip is the relative movement between individual prepreg plies during forming. Interply slip is necessary in virtually all forming of prepreg stacks, and can accommodate two types of stack deformation. Firstly, during the bending of a flat ply stack over a radius (single-curvature forming) each ply must slide over the other, as otherwise high tensile strains would occur in the outermost plies and compressive strains in the innermost plies. Secondly, during forming of a stack over a compound curve, the necessary local intraply shear will be different in adjacent plies with different orientations. Interply slip must occur to allow this.

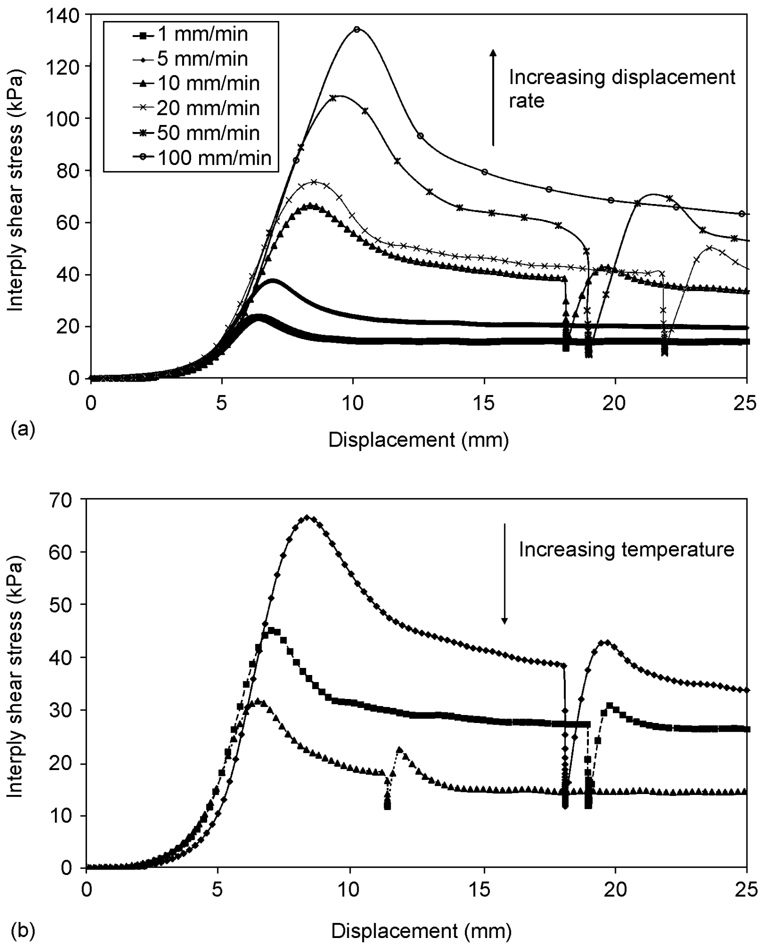


10.1 Apparatus to measure interply slip resistance. (a) Schematic of the apparatus. (b) Photo of the apparatus during a test.

As plies are relatively thin, and are in contact with plies of different orientation, a considerable amount of work may be required for relative movement of the large area of ply interfaces. Resistance to interply slip can be quite high, and is dependent on resin viscosity and the compaction pressure on the stack. Higher slip resistance is experienced under higher compaction pressures. Interply slip resistance is also strongly dependent on temperature, as the viscosity of the resin is a major controlling factor.

To characterise the resistance to interply slippage between prepreg plies, several fixtures including that shown in Fig. 10.1 (Young and Paton 2001) have been used. In the test, the upper plate grips the outer prepreg specimen and the lower stationary plate holds the inner prepreg specimen. The resistance to slip between the inner and outer prepreg specimens is measured and recorded by a tensile test machine. The normal (compaction) pressure on the two specimens may be adjusted using the four calibrated springs through the side plates. The normal pressure remains relatively constant despite small changes in spring length caused by 'bedding in' of the inner and outer specimens.

Figure 10.2 shows typical curves of the interply slip resistance against displacement (Phung *et al.* 2003). In the tests shown here, the prepreg has a high



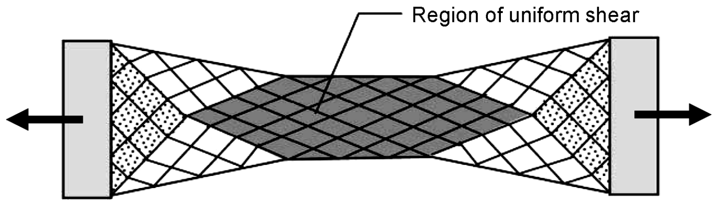
10.2 Interply shear stress for a fabric prepreg: (a) under different slip rates, (b) at different temperatures.

initial static resistance followed by a decrease to a more constant level of resistance. The load oscillations to the right of the plots record intentional temporary stoppages in the test to measure force relaxation.

During forming, it may be necessary for prepreg plies to slip across tooling or diaphragm surfaces. It has been found that slip resistance against these surfaces is similar to that against another prepreg surface.

10.3.2 Intraply shear

Intraply shear, (also called trellising, or extension along the bias of the weave) is the major deformation mechanism that allows an individual prepreg ply to conform to a compound curvature. The resistance to intraply shear, and the

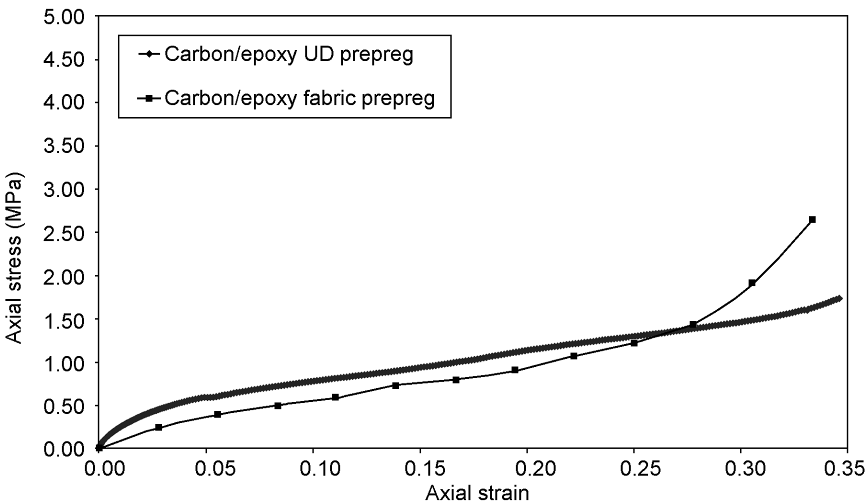


10.3 Schematic representation of a bias extension test fabric coupon, showing the different shear regions.

amount of shear possible before the fabric locks or jams, is dependent on the weave type and tow spacing, as well as resin characteristics.

Both the bias extension test and the picture frame shear test can be used to characterise the intraply shear of prepregs (Young and Paton 2001). However, the bias extension test is easier to conduct. The resin stops the fabric from fraying, almost eliminates inter-tow slip, and keeps the fabric together. Conversely, the picture frame test requires very careful set-up with carbon fibre fabrics, as the fibre is so stiff that tiny fabric misalignments lead to the fibre being loaded in tension during the test, increasing the apparent shear load on the fabric. Thus the bias extension test is preferred. The principle of the test is depicted in Fig. 10.3 (Phung 2004).

Results from bias extension tests on fabric prepregs typically look like the curve shown in Fig. 10.4 (Phung 2004), with three distinct stages in the force-displacement curve. As load is first applied there is some fibre straightening and slippage between the tows, as well as fabric shear. In some cases there also appears to be a 'yielding' effect in the resin as it starts to shear. In the second



10.4 Stress–strain curve for bias extension tests on one ply of ±45 prepreg fabric and two plies [+45, −45] of prepreg tape.

region of the curve, shear occurs at a steadily increasing load. In the third region there is an accelerating increase in load caused by the locking (jamming) of tows with the closure of spaces between tows preventing any further easy rotation of tows towards the loading direction.

It should be noted that the phenomenon of tow locking is easily observed in tests and receives a lot of attention from researchers. However in practical manufacturing situations with prepreg stacks, intraply shear strains rarely reach the level required for locking to occur.

Correlation of forming experiments with simulations suggest that lateral compaction pressure on the prepreg fabric during shearing strongly affects the shear force required. Unfortunately this effect is difficult to measure directly, and a successful apparatus for this is not known to the author.

10.3.3 Fabric bending

A third required deformation mode is out-of-plane ply bending. As the plies are usually quite thin, the bending stiffness of woven prepreg is generally very low in comparison to its in-plane tensile strength, and the prepreg can be formed around tight radii. Ply bending resistance is not usually a significant factor in forming of prepreg stacks. However, as input is required for simulations, bending stiffness has been measured under a static load by a self-weight cantilever bend test (Young *et al.* 2001, Wang *et al.* 2006). The visco-elastic nature of the resin makes the deflection time-dependent. The deflection increases rapidly at first and then slowly approaches an equilibrium asymptote value.

10.3.4 Tow bending, buckling and crimping

In-plane tow bending is required where tows pass between regions of different intraply shear strain, such as shown in Fig. 10.3. Resistance to this leads to intertow slip, followed by tow separation or squeezing in these areas.

Tow bending resistance, however, is very important for a different reason. Tow buckling is a critical deformation mode, but an unwanted one. The most frequent defect in parts made by forming prepreg stacks is a wrinkle (a line of buckled tows). Although small amounts of tow buckling, or tow buckling in a lightly loaded area, may be tolerated, obvious tow buckling normally leads to rejection of an aerospace carbon-epoxy part. Even if the contour of the part is not affected (i.e. the buckles are in-plane rather than out-of-plane) the local failure load of the laminate, especially in compression, will be severely degraded. This makes tow buckling a significant problem during forming. The key problem in prepreg forming could be summed up as 'how to encourage all other modes of deformation while avoiding tow buckling'.

The buckling resistance of the tow is complex to measure, and is imperfectly understood. It is directly dependent on fibre type and size, and tow geometry (especially the degree of crimp), and has a complex relationship to resin viscosity. More work is needed to characterise tow buckling resistance.

10.3.5 Intertow slip

Intertow slip is the relative slippage of tows in the prepreg at their cross-over point. Generally intertow slip is a minor deformation mechanism in prepregs, making only a small contribution to the forming capability of a fabric. Intertow slip is most obvious at prepreg edges where tows can sometimes be separated from their neighbour due to high traction forces. However, one of the benefits of using prepreg is that the fabric edges are, in general, much more stable than in dry fabrics.

10.3.6 Fibre stretching

Generally, carbon reinforcing fibres only stretch at most 1% to 2% before failure. Therefore fibre stretch during forming is minimal and has little influence on the formability of the prepregs. However, woven fabric prepregs may stretch a little in the fibre direction (less than 0.5%) by straightening of the weave crimp, and may be compressed a similar amount in the fibre direction by an even distribution of increased weave crimp, without the strain being easily detected or being considered as a laminate defect.

10.3.7 The influence of temperature and thermal history

As each of the deformation mechanisms are dependent to some degree on the viscosity of the pre-impregnated resin, and the resin viscosity itself is dependent on time and temperature history, prepreg forming properties are time/temperature dependent. Interply slip resistance, intra-ply shear stiffness, and bending stiffness are dependent on viscosity, and thus are initially reduced by increasing temperature in the prepreg. (However, prolonged exposure to elevated temperature will increase resin viscosity as the resin cures.) For this reason it may sometimes be useful to carry out forming at an elevated temperature. However, it should be noted that tow buckling resistance is also reduced at elevated temperature.

Deformation mechanisms in prepreg are substantially viscoelastic. Formed shapes typically revert at least partly towards their original flat shape if removed from the tooling and not restrained. Prepreg deformation is also sensitive to strain rate. A thousand percent increase in strain rate may lead to a hundred percent increase in interply slip or intraply shear load. The time dependency and shape recovery potential is very dependent on the prepreg resin and thermal history.

10.3.8 Stack forming behaviour

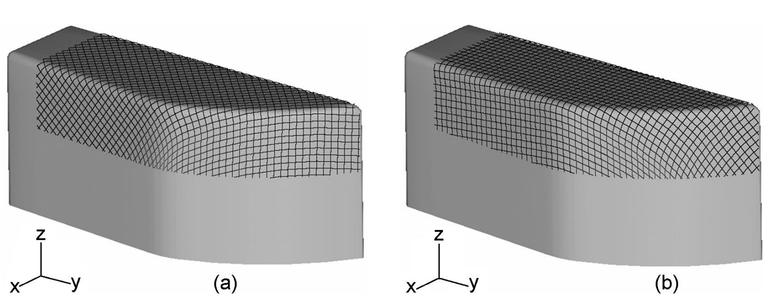
When a fabric is required to conform to a complex shape such as the rib shape in Fig. 10.5, the orientation of the weave controls the local intra-ply shear required. Figure 10.7 shows the shape of a rib for an aircraft control surface leading edge with the drape pattern of a 0º/90º ply (left), and a ±45º ply (right), predicted using the DRAPE simulation software (Bergsma 2000). It can readily be seen that the required shear pattern is different for the two fabric orientations.

These shear patterns predicted using drape simulation software may only be realised by forming single plies under ideal conditions. In multi-ply stacks the resistance to interply slip imposes constraints on local intraply shear, and it is observed that the shear pattern of surface plies in such stacks often does not match that predicted by draping theory. Intraply shear deformation is usually less than predicted. The consequent residual compression stress in the plies may be dissipated by the formation of local wrinkles, or by increased local crimp in the fabric.

10.4 Tape prepreg

The deformation mechanisms for tape prepreg are in many ways similar to those of fabric prepreg. Interply slip behaviour in particular is similar (Phung *et al.* 2003). Out-of-plane bending resistance is higher in the fibre direction, and much lower in the transverse direction.

The important difference is in intraply shear behaviour. Intraply shear resistance is thought to be considerably lower than for fabric prepregs, but is somewhat difficult to measure directly. Bias extension tests on two ply [+45, −45] specimens give similar results to those on a single ±45 fabric prepreg (see Fig. 10.4) and to some extent produce the intraply shear behaviour expected of a pin-jointed net (Potter 2002a), although there is no tow locking effect, and both intertow slip and interply slip become more obvious at higher extensions. However, much of the apparent intraply shear resistance in such bias extension



10.5 Solid model of the leading edge rib tool 'draped' with a fabric at 0/90º and ±45º orientations using simulation software. Locations of maximum shear can be seen for each case.

tests stems in fact from the interply slip between the two unidirectional plies (Phung 2004).

Tape prepreg has an additional deformation mode, transverse stretching or bunching, which can assist the forming of stacks into or over double curved tooling (Potter 2002b). However, the same mechanism can lead to unstable local deformation such as splitting of the surface plies in the forming of tape prepreg stacks: for best results surface plies should not be oriented with fibre direction parallel to any stack edge subject to significant traction. Local microbuckling of tows can also be seen in some cases (Phung 2004, Potter 2002a).

Although there seems to have been less research into the forming of tape prepreg than fabric prepreg, there are good reasons to believe that stack forming technology should be much better suited to tape prepreg than fabric prepreg (Potter 2002b). Certainly the advantages of automated forming methods over hand layup should be greater for prepreg tape than prepreg fabric.

10.5 Forming processes

Forming can be done by a variety of processes. Diaphragm processes and rubber presses are common. Matched dies and folding machinery are also sometimes used. Rollers and matched form dies may be used to form continuous single plies or ply stacks in an automated continuous process forming constant section profiles.

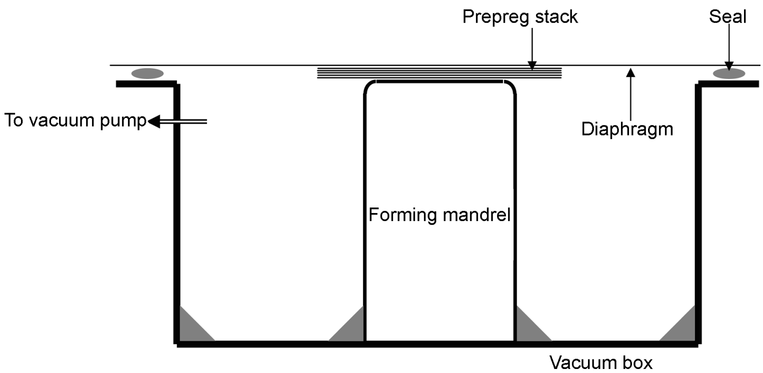
Diaphragm forming may involve a single diaphragm or two diaphragms which encapsulate the preform stack.

10.5.1 Single-diaphragm forming

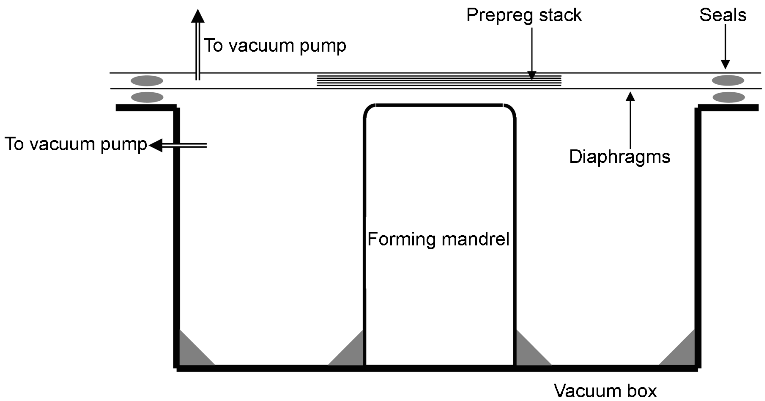
Single-diaphragm forming is most suitable for simply curved shapes such as ribs with straight flanges. The diaphragm is only capable of effectively transmitting forces normal to its surface, making it difficult, using this method, to form shapes with significant double curvature. A forming box arrangement similar to that shown in Fig. 10.6 (Young and Paton 2001) can be used. Air is pumped out of the cavity and the diaphragm deforms under the action of atmospheric pressure.

10.5.2 Double-diaphragm forming

In double-diaphragm forming a common arrangement is similar to that shown in Fig. 10.7 (Young and Paton 2001). The upper and lower diaphragms are sealed together at their edges, and air is removed from the resulting cavity to supply a clamping force to the prepreg stack. This enables a range of forces to be transferred into the stack. Once vacuum is established between the diaphragms, the cavity between the mould and the lower diaphragm is evacuated. The



10.6 Basic tooling arrangement for single-diaphragm forming.



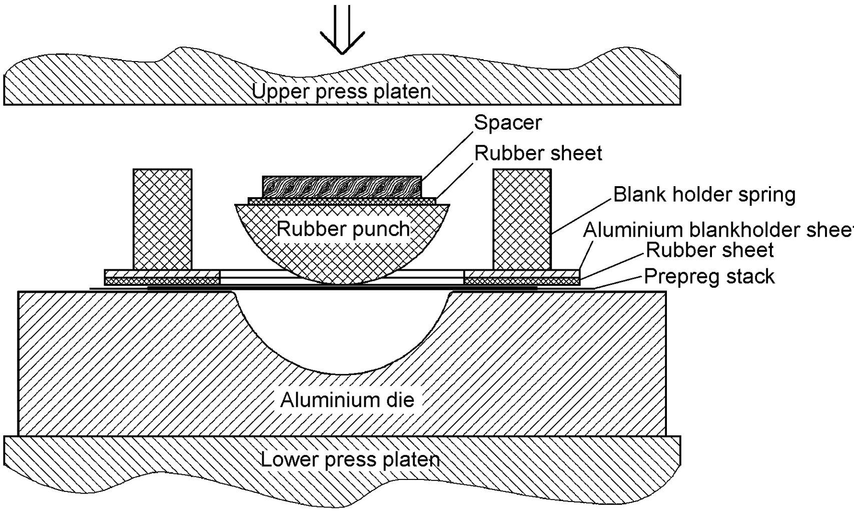
10.7 Basic tooling arrangement for double-diaphragm forming.

diaphragms are then stretched and formed into the box cavity, under the action of atmospheric pressure, taking the prepreg stack along with them.

10.5.3 Rubber press forming

A rubber press is also commonly used to form prepreg stacks. The tooling usually consists of a rubber die and a matching metal die. The rubber tool may be either the male or female tool. A metal male can be used with a rubber female to make simple rib type shapes similar to those shown in Fig. 10.11.

A metal female tool similar to that in Fig. 10.8 can be used to make more complex parts (Piegsa 2003), such as the flanged near-hemisphere shown in Fig. 10.11. The blank holder(s) may be quite complex devices, and must be carefully designed to apply sufficient ‘friction’ in the right places so that the plies are held in tension throughout the forming process, even as the plies slip under the blank holder. Excessive load on the blank holders will lead to excessive punch loads or



10.8 Rubber male forming punch and metal female die with blank holder.

even rupture of the plies. Quite complex parts such as stiffened wing ribs can be made using this sort of process.

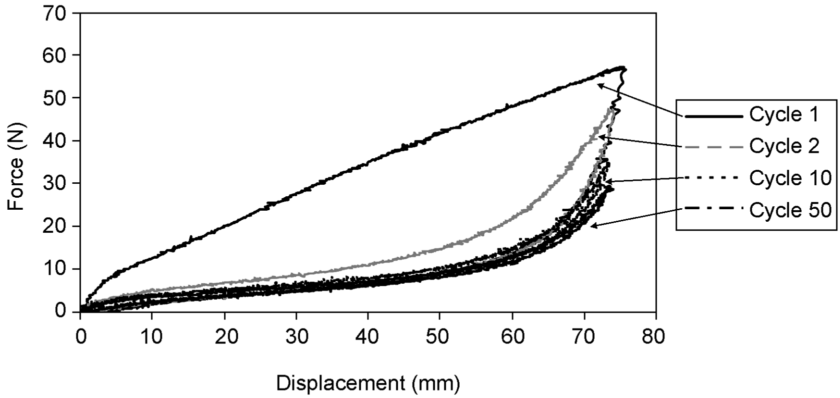
10.6 Tooling and equipment

10.6.1 Vacuum pump or compressor

Most diaphragm forming is done using a vacuum source, as it is generally sufficient to use atmospheric pressure to drive down the diaphragm(s). For double-diaphragm forming, there are two cavities to be evacuated, and for best results the pressure in these cavities should be controlled separately. The forming box cavity must be evacuated to pull down the diaphragm(s) and the rate of evacuation naturally controls the forming rate. Unless very rapid forming is required for economic reasons, the cavity is normally evacuated in a few minutes. High vacuum is not necessary. The cavity between the diaphragms may require higher vacuum before and during forming, in order to ensure continuous clamping pressure on the stack, and also to remove air, moisture and volatiles from the prepreg stack. Where more force is required, it is practical to use an inflatable bladder to pressure a single diaphragm against a stack and hard mandrel. A rubber or rubber-faced punch may also be used.

10.6.2 Heat sources

For many applications the prepreg needs to be heated to ensure it is at the optimum temperature for forming. Many heat sources can be used. Radiant heating devices such as infra-red lamps are particularly effective, as carbon



10.9 Force-displacement behaviour of silicone rubber at up to 300% strain after different numbers of cycles.

prepreg has a matt black surface, and reasonable heat conductivity. Where stacks are thick, radiant heating may be ineffective or insufficient, and it may be necessary to heat the stack from both sides, or heat the forming mandrel itself.

10.6.3 Diaphragm materials

For forming prepreg stacks, two types of diaphragm are common. Silicone rubber sheet, a hyperelastic material, is perhaps the most popular. High-temperature polymer films, which behave in an elastic-plastic manner during deformation, are also used. The choice of diaphragm depends on both circumstances and preferences.

Silicone rubber diaphragms are much more expensive, but can be re-used many times which saves costs in the long term. This makes them especially suitable for manufacturing smaller preforms, and higher manufacturing rates. Silicone rubbers also exhibit some 'permanent set' due to the Mullins effect. Figure 10.9 (Bibo and Paton 1999) shows the typical stress-strain behaviour of a silicone rubber used for diaphragm forming, and the Mullins effect.

Expendable high-temperature polymer diaphragms can only be used once. They can be prone to leaks though small pin-holes. The quite different stress-strain behaviour of these two diaphragm materials means that the design of the forming process can be dependent on the type of diaphragm.

10.7 Diaphragm forming tooling

The diaphragm forming process is most efficient when many parts can be formed at once. Sets of forming mandrels may be permanently placed within a dedicated forming box, especially if the parts are complex. In this case the cavities and sealing rim may be carefully designed for optimum efficiency. The box must, of course, be vacuum tight, and able to withstand normal loads of one atmosphere without deformation or collapse.

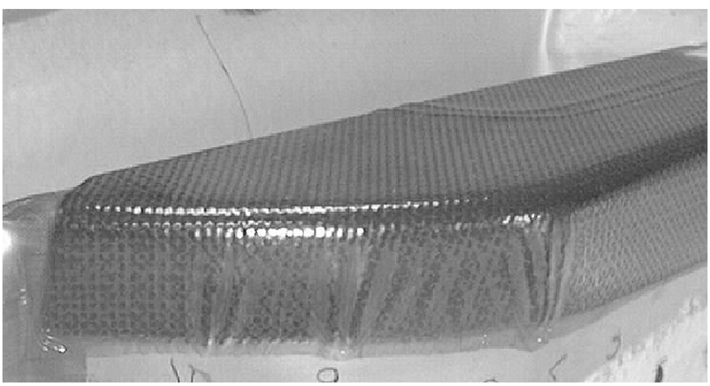
Alternatively, a larger generic forming box may be used, into which forming mandrels are placed and grouped as required. This approach may reduce tooling cost, but is more suited to simpler parts and lower throughput, as it is more difficult to optimise the forming of individual parts when all the tooling has to be removed and replaced frequently.

Whichever type of forming box is used, the box has vacuum connections and quick seal provisions on its flanges. It may have a folding lid or frame with integral diaphragm. Where higher temperatures are used for forming, the part mandrels need to be dimensionally stable and built from the usual tooling materials – steel, nickel, Invar or carbon-epoxy. Internal tooling which is solely used to shape the cavity or support the diaphragms may be made of less stable materials.

10.8 Potential problems

When forming carbon-epoxy prepreg stacks, the most common defects are various types of wrinkles. One type can be found in the inner plies of a radius, even in simple-curved shapes, where they are caused by the bending of the stack placing the inner plies under a compression force normal to the axis of the corner.

A second common type is an out-of-plane wrinkle involving all the plies in the stack, as seen in Fig. 10.10. These wrinkles are caused by the resistance of the plies in the stack to the shearing necessary to accommodate a shortened 'path length'. (After the forming operation shown in Figs 10.5 and 10.10, the 'path length' along the curved portion of the rib flange is less than the 'path length' of the section of flat stack from which it was formed.) This may be because the many interfaces in a quasi-isotropic layup have, in total, too much resistance to



10.10 Wrinkles in the curved flange of a rib perform.

slip to allow the individual intraply shear required, or because the required in-plane shear cannot be accommodated by the local fabric orientation. Such wrinkles are likely to result in the part being rejected, because the local part thickness is too great, or the fibre orientation is locally incorrect.

Where matching hard tooling is used for forming, or a hard tool and soft tool combination, it is possible to break fibres, leading to rejection of the part. In diaphragm forming, this is rare – more common is a situation where the strength and stiffness of the plies, and the geometry of the tooling, result in bridging of the plies or incomplete forming of the stack around the tooling.

10.9 Process capabilities

Diaphragm forming is very successful for forming parts such as ribs and spars over male tools. These parts typically have a 'C'-shaped cross-section. Straight flanges are the easiest to form, and may often be formed using a single diaphragm, or in matched moulds. However, convex-shaped flanges with a radius as tight as 50 mm can be successfully formed from flat prepreg stacks by double-diaphragm forming. Parts with a mild concave flange may also be formed in the right conditions. In this case the limiting factor will usually be fibre bridging, so the orientation of the fibres with respect to the tooling is absolutely critical.

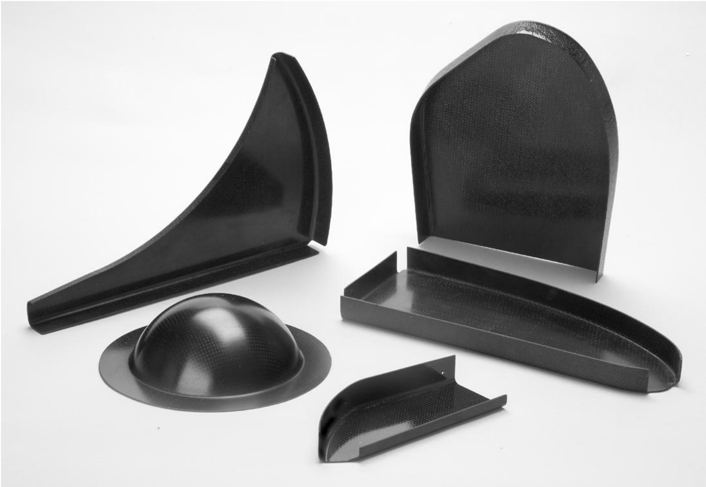
The double-diaphragm forming process as used by the Cooperative Research Centre for Advanced Composite Structures is capable of forming most of the typical rib and spar shapes found in the substructure of aircraft control surfaces. The shapes formed have included those in Fig. 10.11. Spar shapes with joggles in the flanges can also be formed. The critical factors are normally the length of the flange, the thickness of the stack, and the curvature of the flange, if any. As these increase, forming becomes more difficult.

The part at lower left in Fig. 10.11 is a flanged dome shape formed using a rubber male punch and a metal female tool with blank holder.

10.10 Future trends

Forming of flat, prepreg stacks into shaped preforms can be very successful if the deformation requirements can be understood. Although the fabric stack is in practical terms inextensible in any fibre direction, the intraply shear, interply slip, and ply bending deformation modes enable many shapes to be successfully formed. Some aircraft control surface rib shapes are actually easier to form in prepreg than in aluminium. The forming process is also easier, with lower tooling costs than the thermoforming of thermoplastic composites, as the temperatures and loads required are substantially less.

The technology of forming reinforcement stacks is likely to become much more important as efforts continue to lower the cost of continuous-fibre



10.11 Prepreg preform shapes formed at CRC-ACS (clockwise from top left): a DDF rudder leading-edge rib with a concave flange; a DDF section of a rudder closure rib; a DDF flap leading-edge rib; a DDF rudder leading edge rib; a flanged dome shape formed using a rubber male punch and a metal female die with blank holder.

reinforced polymer composites. Widespread introduction of carbon-epoxy composite into the automotive industry, for example, would appear to require robust forming technology. Whether this forming technology involves dry fibre fabrics, thermoset prepregs or thermoplastic laminates, will depend heavily on the economics of the different material forms, and recyclability requirements, as well as the forming technology.

The lack of any plastic deformation mode for the continuous reinforcement fibres is, however, a significant hindrance. It seems likely that some low cost and robust form of long discontinuous fibre prepreg will emerge in the near future which will allow a certain degree of effective 'fibre extension' to occur during forming. This would significantly increase the number of shapes that could be formed, and give a tremendous boost to composites forming technology.

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