Measurement Good Practice Guide No. 38

Fibre Reinforced Plastic Composites – Machining of Composites and Specimen Preparation

Andrew Davies, Andrew Foreman,
Richard Shaw and Graham Sims

Defence Evaluation Research Agency, Farnborough and
National Physical Laboratory, Teddington

Abstract:

The confidence placed in design data obtained from testing composite materials can depend greatly on the quality of the specimen used. Although, in principle the use of rectangular blanks as the staring point in most cases suggests specimen preparation is straightforward, there are many aspects that affect the quality of the measured data. For example, for unidirectional material loaded in either tension or compression, it is necessary to transfer the load into the specimen via protective tabs as it is not possible to use threaded or pin connections; or to use high grip pressures, due to the low interlaminar and transverse strength. Hence end tabs must be used that are well bonded to the specimen to avoid premature failure. In addition, for compression testing of these relatively thin laminates, as well as the test machine loading axially, the tabbed specimen must be symmetrical.

The guide provides background information on all stages and aspects of machining and specimen preparation and reviews Good Practice in the preparation of specimens of composite materials, which in this context are polymeric matrices, both thermoset and thermoplastics, reinforced by fibres with a length greater than 7.5 mm in the starting material or compound. In recognition, of the wide range of materials involved and the range of machining equipment in use, the guide concentrates on good practice procedures and is not prescriptive on feeds, speeds, etc. Included are experiences gained during the research programme covering machining trials and the results of industrial reviews of current practices with results given from Round-Robin participation. Also included, as an annex is a guide procedure that will be proposed as a future standard similar to ISO 1818 that deals with unreinforced or short and particulate reinforced polymers. Attention is also drawn to ISO 1268 for test plate preparation as the source of most test specimens.

The preparation procedures have been incorporated onto a laminated card, which can be used as a checklist using a non-permanent marker, or photocopied for completion as part of the specimen preparation QA records.

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National Physical Laboratory
Teddington, Middlesex, UK, TW11 0LW

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For further information please contact:
Materials Enquiry Point
Tel: 020 8943 6701
Fax: 020 8943 7160
E-mail: materials@npl.co.uk
Website: www.npl.co.uk

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1. Introduction

This Guide establishes the general procedures to be followed when preparing test coupons from fibre reinforced plastic composites test plates or from finished products. It covers machining, surface preparation and end-tab bonding operations. In order to establish a basis for preparation of reproducible and acceptable quality coupons, in addition to the general procedures, exact procedures need to be selected or specified in conjunction with the relevant material specification and/or by the relevant standard test method. If sufficiently detailed procedures are not specified in a standard, it is essential that the interested parties agree on the preparation conditions to be used.

The preparation of the following types of test coupons are covered:
- Rectangular coupons, with and without end-tabs.
- Machined coupons, as above, containing holes or notches.
- Dumbbell coupons, plain.

The text applies to all types of reinforced thermosets and thermoplastics, as appropriate. Preparation of turned round specimens (cf metals where often the preferred specimen type) is not covered as normally used in the as-formed condition (e.g. pultruded rods according to ISO 3957). For machining of low fibre volume fraction materials ISO 2818 (*Plastics – Preparation of test coupons by machining*) should also be consulted.

The Guide provides background information on all stages and aspects of machining and specimen preparation. Also included are experiences gained during the research programme covering machining trials and the results of industrial reviews of current practices with results given from Round-Robin participation.

1.1. Test panel manufacture

The majority of testing is undertaken using specimens cut from a test panel and travellers, rather than from the product itself. ISO has recently developed a multi-part standard that covers preparation of test panels in a consistent manner for all established processing routes. As new processes are developed such as, resin film infusion, then a new or modified part of the standard will be produced.

ISO 1268 -1 Fibre reinforced plastics – Test plates manufacturing methods:
Part 1: *General conditions*
Part 2: *Contact and spray-up moulding*
Part 3: *Wet compression moulding*
Part 4: *Moulding of preimpregnates*
Part 5: *Filament winding*
Part 6: *Pultrusion moulding*
Part 7: *Resin transfer moulding*
Part 8: *Moulding of SMC, BMC*
Part 9: *Moulding of (GMT) glass mat thermoplastics*

1.2. Standard test methods

This guide is principally aimed at preparation of coupon specimens for the test methods given in Table 1 and equivalent test methods or specimens, but the principles can be applied more widely.

Table 1 Relevant Standard Test Methods

Property	Standard ISO Test Method	Similar methods
Tension – UD (Unidirectional)	BS EN ISO 527-4	ASTM D3039
Tension – Multidirectional	BS EN ISO 527-5	ASTM D3039
Compression	BS EN ISO 14126	ASTM D3410
Shear – double v		ASTM D5379
Shear – double notch	ISO NWI proposal	ASTM D3846
Shear – Interlaminar	BS EN ISO 14130	ASTM D2344
Shear – in-plane/tension	BS EN ISO 14129	ASTM D3518
Shear – in-plane/plate twist	BS EN ISO 15310	
Flexure	BS EN ISO 14125	ASTM D790
Pin – bearing	ISO NWI proposal	ASTM D5961
Open hole compression	ISO NWI proposal	
Open hole tension	ISO NWI proposal	ASTM D5766

1.3. Machining and ancillary equipment

There are two main machining operations used for preparation of fibre reinforced materials, slitting actions to produce coupon blanks, and finishing operations to incorporate holes and notches of various designs. These actions are normally undertaken using:

- Slitting or sawing machines.
- Drilling machines.
- Milling machines.

There are also less established machining techniques for composites that include:

- Water jet.
- Laser.
- Electrical discharge machining (EDM).

The use of these machines and associated drill bits etc. is discussed in Sections 3 and 4.

Additional equipment may include grit cabinets for surface preparation of coupons for subsequent bonding of end-tabs (see Section 7) and clamping/alignment jigs at different stages. For hot cured adhesives a suitable oven is required.

1.4. Inspection procedures

Following preparation of the test coupon it is important to check the dimensional and machining quality are within the test method limits. Any coupon showing a measurable or observable departure from the requirements given in the relevant test standard shall be rejected or machined to the correct size and shape before testing. Some ancillary equipment (e.g. magnifiers, callipers etc) is required to make these checks.

More detailed information regarding the quality of the test coupons is given in Section 8. The final test report (see Section 8 and Annex 3) should ensure the trace ability of the starting materials and all subsequent operations.

1.5. Adhesives, tab materials and ancillary materials

Glass fibre reinforced plastic laminates containing a square weave woven fabric, or 0°/90° cross-plies, set at 45° to the coupon axis are recommended. Other materials can be used for particular circumstances as noted in the appropriate test method standard. Alternate tabbing material, tabs made from material under test, mechanically fastened tabs, unbonded tabs or friction materials (emery paper, grit paper or fine finish grip faces) shall be shown to give a least equal strength values and no greater coefficient of variation (see ISO 527-5, clause 10.5) than the recommended tab material before use.

2. Outline procedure

This Guide specifies the machining and bonding procedures to enable samples of fibre reinforced plastic composites to be prepared as acceptable test coupons, in agreement with the requirement defined in the relevant test method. The material sample may be available as a test plate(s) or cut from suitable areas of a final product. Three preparation procedures are available, as follows:

Procedure A End-tabbing (nb excluding metal end-tabs) is applied to a test plate, or a section cut from it, prior to machining into separate coupons.

Procedure B Individual coupons are machined and then individually tabbed.

Procedure C Untabbed, or loose tabbed coupons are prepared.

The exact shape dimensions and tolerances of the test coupons are given by the test method for the particular property required (see Table 1).

The test coupons are normally machined from plates made according to ISO 1268 or by agreed alternative methods, or cut from suitable flat areas of final products. Due to the anisotropy of most fibre reinforced plastic composites the position and direction of the cutting of coupons must be recorded on a cutting plan according to the “zero degree” direction marked on the test plate, or by a defined direction in a final product. A scheme is given in Annex A of ISO 1268-1 for indicating the direction and stacking sequence of lay-ups in laminated materials, and for marking the “zero degree” direction.

The basic steps are to:

- Confirm, or determine, the type of composite material under consideration according to Annex 1.
- Record the quality and manufacturing conditions of the supplied test material.
- Determine the required coupon sizes, number of coupons, tolerances, etc. as defined in the appropriate test method standard (see Bibliography for full reference to some relevant ISO test method standards).
- Select the end-tab material, adhesive and surface preparation applicable depending on the test conditions (e.g. test temperature, environmental conditioning) according to Section 5.
- Determine if Procedure A or B is required for the addition of end-tabs from the appropriate test method standard (see Figure 1). Use Procedure C for untabbed or loose tabbed coupons.

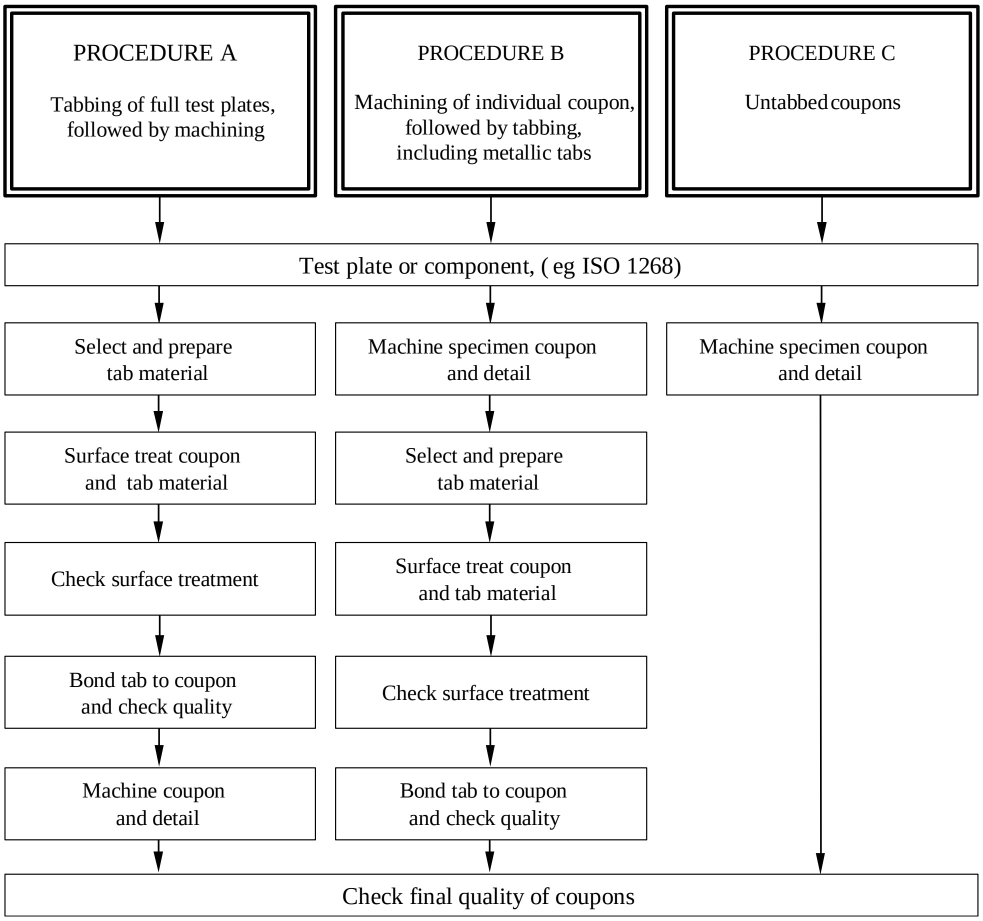


Figure 2.1 Flow chart for different specimen preparation procedures.

Note*: For metallic end-tabs, Procedure B is used to avoid machining metal and composite at the same time.*

2.1. Procedure A

The main aspect of Procedure A is that end-tab material strips are machined sufficient to bond across the width of the sample test plate, in accordance with the relevant test method, and the tabbed test panel is machined into coupons when the adhesive has cured. Detailed machining of holes and notches is then undertaken on the individual coupons.

2.2. Procedure B

The main aspect of Procedure B is that the test plate is machined into coupons and tabbing applied to individual specimens. Any detailed machining necessary would also be undertaken prior to tabbing.

2.3. Procedure C

Procedure C is for untabbed and loose tabbed coupons (nb. tabs may be reusable) and is similar to the first stages of Procedure B.

3. Techniques for machining rectangular blanks

3.1. Conventional techniques

In all cases take the following precautions:

- Avoid working under conditions that would create a large build-up of heat in the test coupon. It is recommended that a coolant be used. In particular a 5% oil based coolant mixture. If a liquid coolant is used, dry the test coupons immediately after machining.

- Check that cut surfaces of the test coupon are free from machining defects.

- When using a hydraulic/pneumatic clamping arm, pressures between 3 to 5 bar normally provides adequate clamping force.

3.1.1. Machines

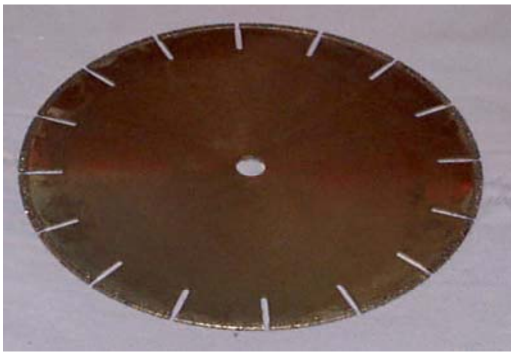
The machine shall be capable of achieving the required speeds and feeds quoted, suitable machines are:

- Circular saw.
- Milling Machine (CNC or Manual), see Section 4 for further information.

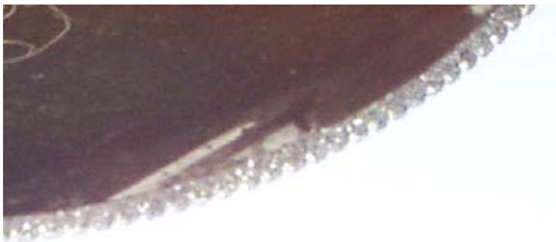
3.1.2. Tool types

Circular wheels of 2 mm thickness are normally sufficiently stable to provide the required tolerance on coupon dimension. Thicker wheels result in more wastage of material without any other benefit. Wheels in use are normally 150 mm in diameter or larger.

Standard wheel - Solid



Standard wheel - slotted



Aramid fibre laminate cutting wheel - serrated

Figure 3.1 Circular saw types

3.1.3. Circular wheels

Table 3.1 Circular saw wheel data.

Construction	Coating	Diameter (mm)	Thickness (mm)
Solid	PCD	≥150	2
Solid	PCD 40Grit	≥150	2
Slotted	PCD 40 Grit	≥150	2
Serrated	PCD	≥150	2

The wheel designed for aramid fibre reinforced materials is similar in construction to the solid wheel shown above, but has serrated cutting edges on the face to allow for a cutting action as well as grinding.

3.1.4. Cutting speeds and feeds

Table 3.2 Circular saw wheel machining data.

Tool Type	Diameter (mm)	Material Thickness (mm)	Spindle Speed (rpm)	Feed Rate (mm/min)
Circular PCD	≥ 150	1-10	1500-5000	500-1500
Circular PCD Sloted	≥ 150	1-10	1500-5000	500-1500
Circular Serrated PCD	≥ 150	1-10	1500-5000	500-1500

3.1.5. Operator experiences

The results given are of trials using three different wheels for a range of composite materials. The surface finish was measured using a low-cost portable talysurf, which scans automatically over a 5 mm length on the cut surface. Surface finishes obtained are shown in Table 3.3 below.

Table 3.3 Achievable surface finish for different FRP materials using different wheel types.

R_z µm	**Wheel type**											
	Solid				**Slotted**				**Bennett**			
Material / Feed	**500 mm/min**		**1500 mm/min**		**500 mm/min**		**1500 mm/min**		**500 mm/min**		**1500 mm/min**	
Carbon fibre/ epoxy woven	7.9	9.1	10.2	12.5	14.3	13.6	15.1	12.6	3.5	5.1	6.1	5.2
Glass fibre fabric/epoxy	8.3	8.1	9.4	10.2	15.4	10.9	14.9	11.6	6.3	5.5	4.4	7.1
SMC (glass fibre/ filler)	9.6	5.8	11.5	7.1	9.1	10.8	10.8	9.6	3.4	5.2	4.5	4.0
Short glass fibre/ nylon	7.6	7.3	n/a	n/a	n/a	n/a	n/a	n/a	5.3	3.0	7.6	5.1
GMT (glass fibre mat/ PP	n/a	n/a	7.6	8.1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Long discontinuous glass fibre/ PP	n/a	n/a	17.2	7.4	n/a	n/a	20.9	18.5	4.5	6.5	8.4	6.0
Pultrusion glass fibre/ Polyester	15.2	14.6	17.2	12.2	14.9	15.3	21.5	15.6				

N/A = surface was damaged by melting or cut was aborted due to melting of the specimen.
nb. Results given are an average of four readings from both sides of the coupon.

The solid circular polycrystalline diamond (PCD) blade preformed the best on a range of materials. A spindle speed of 3500 rpm and a feed rate of 700 mm/min were found to be best for a range of materials.

When machining aramid (e.g. Twaron, Kevlar) fibre reinforced system a solid circular PCD wheel can be used, but the test plate must be placed between sacrificial material (glass-fibre fabric/epoxy, as used for tabs, Tufnol, or MDF) in order to prevent delamination and ‘fuzzing’ of the outer plies.

3.2. Unconventional techniques

Three "unconventional" methods of machining, not routinely used for composites are described in this section.

3.2.1. Abrasive water jet

Water jets can be used with or with out abrasive. An abrasive jet uses water that is pressurised up to 2750 bar and forced through a small synthetic sapphire orifice at between 500 m/s to 900 m/s. Garnet abrasive is then pulled into this high-speed stream of water in a long ceramic mixing tube (Figure 3.2). A stream of abrasive laden water exits the tube and is directed at the material. Machining occurs by a grinding process.

The technique is suitable for all machining operations: - slitting, drilling and turning. Water jet machining eliminates many of the problems associated with conventional machining. Dust is eliminated through a phenomenon known as "jet entrainment". As the high velocity water mixes with the air, a vacuum is formed, trapping any dust, that is collected with the water.

There is no heat-affected zone (HAZ), although some reinforcements (e.g. carbon fibres) can conduct the heat away from the edge in to the middle of the component causing melting or charring of the material (Figure 3.2).

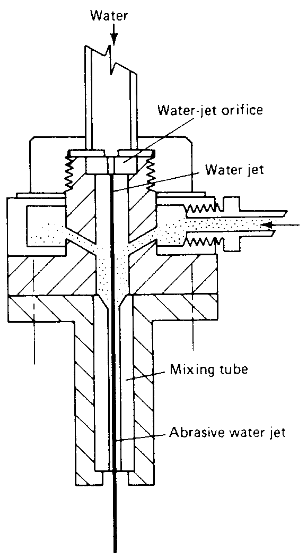


Figure 3.2 Abrasive water jet cutting head

The accuracy of the cutting path, however, depends primarily on the precision of the manipulator system and only indirectly on the abrasive water jet parameters.

3.2.2. Operator experiences

A variety of materials: - carbon, aramid, glass fibre reinforced plastics and lower grade sheet moulding compounds (SMC) were machined by various companies.

Unfortunately the cutting parameters used were not supplied, therefore a quantitative assessment of the cutting parameters was not possible.

The water jet successfully machined composite material of thickness ≤ 3 mm, however, in thicker sections slight tapering of the cut is seen as the material being machined deflects the jet. Lowering the traverse rate of the cutting head across the specimen can reduce this effect.

The specimens machined showed some signs of damage, mainly fibre pullout and delamination caused by the shearing action of the jet. With careful optimisation of the cutting parameters this damage could be reduced significantly.

Optimisation of abrasive water jet parameters such as water jet pressure, velocity, abrasive grain size (and material) distance from material and angle of contact to achieve relatively high traverse rates, low levels of striations are all important if the technique is to be employed cost-effectively.

3.2.3. Laser machining

The laser beam is focused to a very small spot diameter that reduces the size of the heat affected zone (HAZ) and any damage. Laser machining is a non-impacting and non-contacting method involving almost instantaneous vaporisation of the material to form the cut. Suitable laser types are CO_2 and NdYag, which have sufficient power and can be used continuously.

As for water jet machining heat is transferred to the bulk material for some reinforcement types. This effect is more dramatic when cuts are made perpendicular to the fibre direction as the fibres transfer heat further into the bulk material (see Figure 3.3).

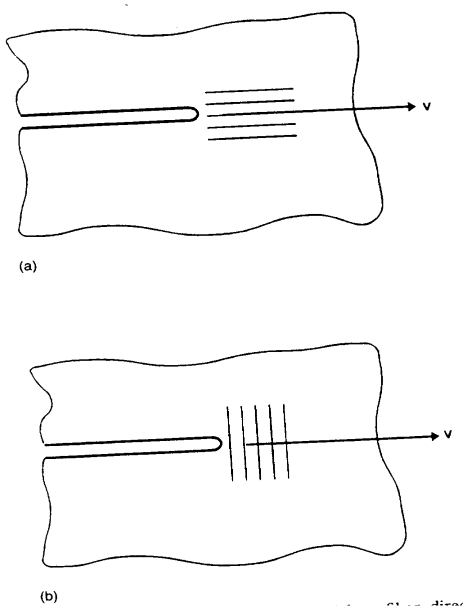


Figure 3.3 Heat Conduction in UD Specimens, Cutting Direction (a) parallel to fibres (b) perpendicular to fibres

3.2.4. Operator experience

In order to assess the heat transfer effect and attempt to quantify the size of the HAZ, laser machining was completed on UD glass and carbon fibre/epoxy. Glass transition temperatures (T_g) were determined for samples taken at various distances from the laser cut edge using differential scanning calorimetry (DSC). Note that the T_g of the plain (i.e. uncut) material was measured as 118 °C and 216 °C for the glass fibre (GRP) and carbon fibre reinforced material (CFRP) respectively. The results are shown in the Table below.

Table 3.4 T_g measurements for laser cut specimens (°C).

	Material		
Distance form cut (mm)	**GRP epoxy**	**CFRP (Cut perpendicular to fibre direction)**	**CFRP (Cut parallel to fibre direction)**
0	118	239	238
1	117	239	236
2	120	237	229

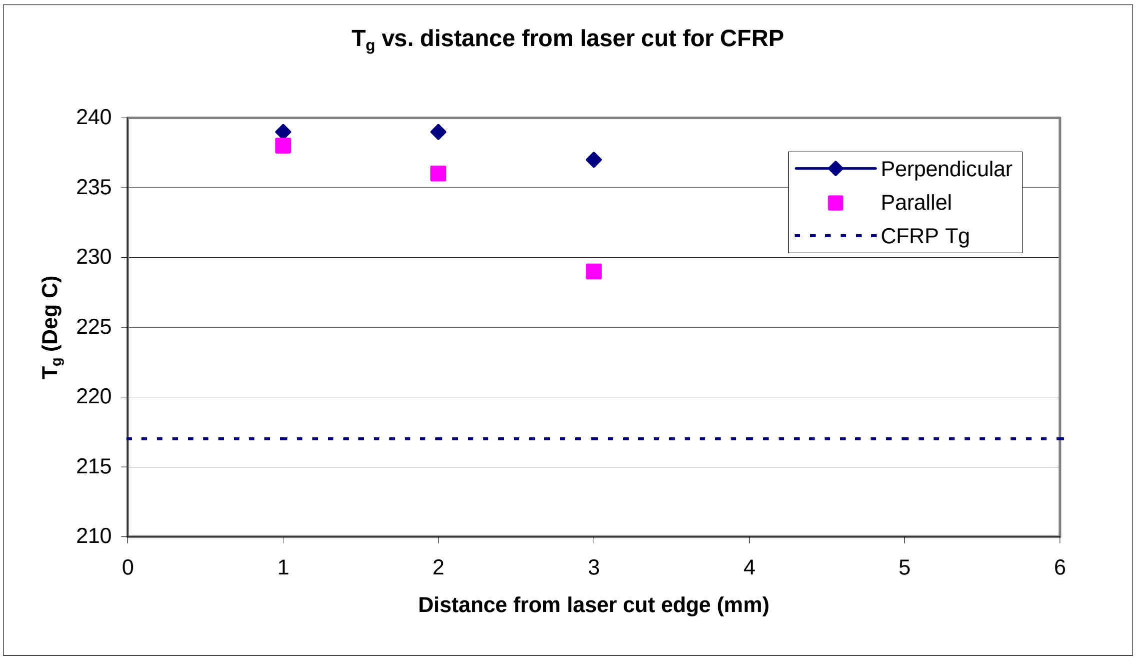


Figure 3.4 T_g vs. distance from Laser cut (°C).

Table 3.4 above shows there was no significant change in T_g for the glass fibre reinforced material compared to uncut, suggesting there was minimal conduction of heat into the specimen. However, for the carbon fibre reinforced specimen there was evidence of heat conduction into the bulk composite. The effect very near to the cut edge was independent of how the laser cut was made. It appears the heat has locally advanced the composite cure state. Figure 3.4 shows the effect remains significant further from the cut when the machining was perpendicular as the fibres are more easily able to carry the heat in the matrix material. Extrapolating the results suggest a HAZ (in this case defined as where 'cut T_g' equals 'uncut T_g') of approximately 4 mm for the parallel cut and 6 mm to 7 mm for the perpendicular cut.

To conclude, research has been conducted on the use of lasers to machine composite materials. Evidence was found of both a heat affected zone and preferential directions of heat conduction through the material. Due to the large differences in the vaporisation temperature of the resins and the fibre, some degradation of the matrix will occur, resulting in melting and charring of the matrix. Laser machining is essentially a clean operation, but because of the thermal degradation of the matrix some volatiles may be emitted and hence adequate ventilation should be allowed. With careful optimisation of the laser cutting parameters, it should be possible to minimise the amount of edge charring, especially in thinner specimens (~2 mm).

3.2.5. Electrical discharge machining (EDM)

A simplified explanation of this complex process defines EDM as a method of machining conductive materials with a series of electrical sparks in the presence of a dielectric. Two basic methods are used. With the die sinking method, the form of the tool is mirrored into the work piece, while the travelling wire electrode process, ruled surfaces corresponding to the trajectory of the wire electrode are produced.

3.2.6 Operator experience

Two machining companies were given 3 mm thick, woven 920/T800 CFRP specimens to machine. It was found by both companies that surface of the composite had to be abraded to remove the outer resin layer to enable a spark to be initiated.

One of the companies, using a conventional oil dielectric, found that as the material sparked, the molten layer of material built up and the gap between the electrode and the substrate was diminished, eventually extinguishing the spark. This phenomenon is called the “recast layer”. The machining process consists of spark-melt-flush-spark-melt flush thousands of times a second, if the dielectric cannot flush away the composite debris, then after each cycle a minute quantity of the molten material is drawn back on to the substrate surface by surface tension. The layer is highly carbonaceous in nature.

Just below the recast layer is the heat-affected zone (HAZ). The extent of both the recast layer and HAZ depends chiefly on the current used sparking frequency and the thermal conductivity of the machined material.

The other machining company continued research using its Watersparc® EDM machine. This technique uses de-ionised water as a dielectric, due to its lower viscosity (compared to oil) it is able to remove debris at a higher rate allowing continuous sparking of the substrate. Using Watersparc® wire EDM technology, holes of 0.2 mm diameter were able to be drilled both through the thickness and width of the specimen.

Electro discharge machining relies on the formation of a spark being created between the work piece and the electrode. For this to happen the work piece must be electrically conductive hence, not all composites can be machined. From research carried out by two EDM companies it has been found that carbon fibre/epoxy composites can be machined, but the success of the process depends on the constituents of the composite and the dielectric used.

There were signs of resin degradation (melting) on the surface of the specimens, and slight charring (although less than with laser machining). EDM as with laser and to some extent abrasive water jet machining, produces better results with thinner specimens (<2 mm). It is capable of very intricate machining operations, but, from the trials carried out, it would be best used at drilling through composites. EDM is a very clean process, all of the machining operations being carried out in a dielectric bath.

4. Techniques for machining details (holes, notches, dumbbell coupons)

4.1. Drilling operations

Avoid working in conditions where large amounts of pressure are applied to the drill, a test hole should first be drilled in a sacrificial coupon to assess whether backing material is necessary for use with the particular drill and the current condition of the drill. Backing material in the form of a similar material (glass-fibre fabric/epoxy, as used for tabs, Tufnol, or MDF) can be used in order to prevent delamination and poor quality holes. The backing material should be held firmly against the back face of the coupon being drilled. It is recommended that a 5% oil based coolant mixture be used.

Drills should be checked for wear at regular intervals, as worn drills will cause delamination and poor quality holes.

The coupon should be held in a vice or clamped in such a manner to prevent movement of the plate during drilling, and to maintain firm contact with the backing material (if used).

4.1.1. Machines

Suitable machines are:

- Pillar Drill (good quality)
- Milling Machine (CNC or Manual)

These normally would have the capabilities of achieving the speeds and feeds in ranges similar to those given in this guide.

4.1.2. Drill types

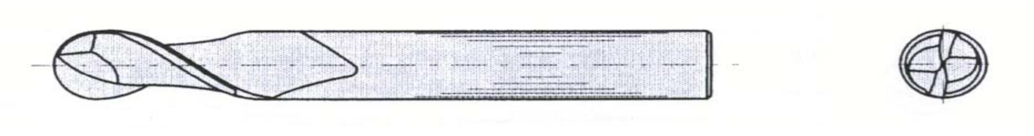


Figure 4.1 Ball nose drill.

Solid Micrograin Carbide drill with radiused tip to prevent delamination on entry and exit faces.

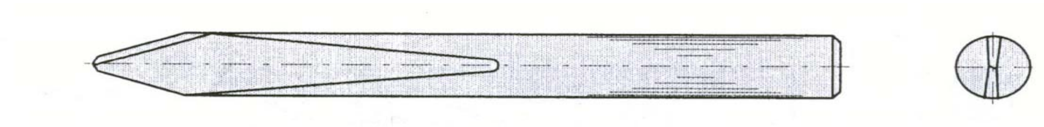


Figure 4.2 Dagger drill.

Solid Micrograin Carbide drill with high edge strength to minimise wear, long tapered point reduces delamination on entry and exit faces.

Figure 4.3 Klenk drill.

Carbide drill with three-point configuration to reduce wear and prevent delamination on entry and exit faces.

4.1.3. Operator experiences

To investigate drill life three different types of drill were used to drill holes into a quasi-isotropic carbon/fibre material, each drill was used until wear was evident on the tool.

Table 4.1 Drill cutting speeds and feeds.

Tool Type	Hole Diameter (mm)	Material Thickness (mm)	Spindle Speed	Feed Rate	Number of holes before tool wear
Klenk Drill	6.00 ± 0.01	3-6	300-800 rpm	≈12 mm/min by hand	≈ 60
Ball Nose Drill	6.00 ± 0.01	3-6	50-250 m/min	0.01-0.05 F/tooth	≈ 100
Dagger Drill	6.00 ± 0.01	3-6	50-150 m/min	0.01-0.05 F/tooth	≈ 100

a) Ball nose drill.
Performed well at 3500 rpm, and 150 mm/min on carbon fibre reinforced epoxy using coolant. Backing material was only required for drilling of quasi-isotropic material.

b) Dagger drill.
Performed well at 3000 rpm, and 100 mm/min on carbon fibre reinforced epoxy using coolant. No backing material was required for drilling of quasi-isotropic material.

c) Klenk drill.
Performed well at 475 rpm with a manual feed rate of approx. 12 mm/min on carbon fibre reinforced epoxy using coolant. Backing material was required on all materials to prevent delamination.

4.1.4. Hole position

The accuracy of the hole position is highly dependant on the skill of the operator involved and the type of machine used. Greater accuracy was obtained using the CNC machine due to its close positional control that allowed the drill to be accurately aligned on the coupon centre line. If more time is dedicated to setting up the coupon on a pillar drill, it is also possible to obtain an accurate hole position by allowing for the width of each individual coupon (within 0.1 mm tolerance on position).

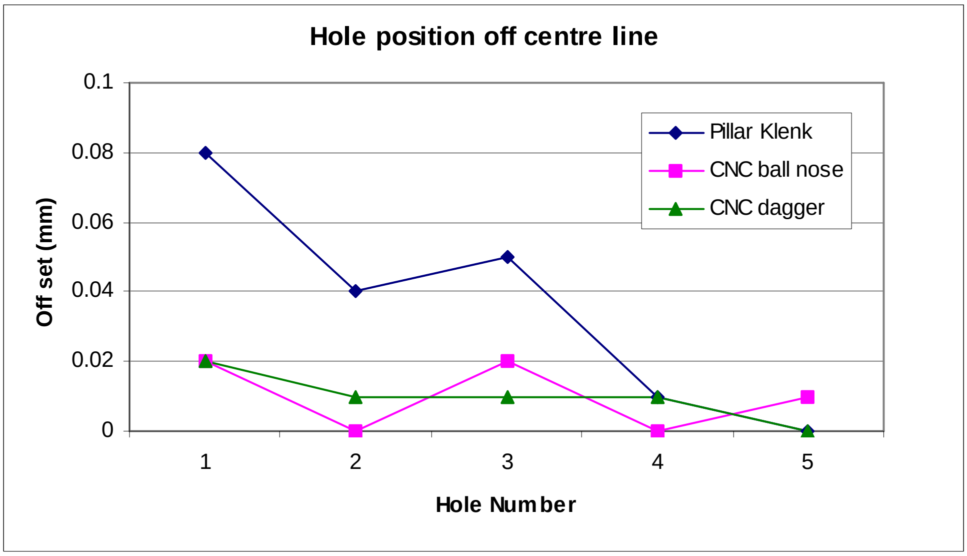
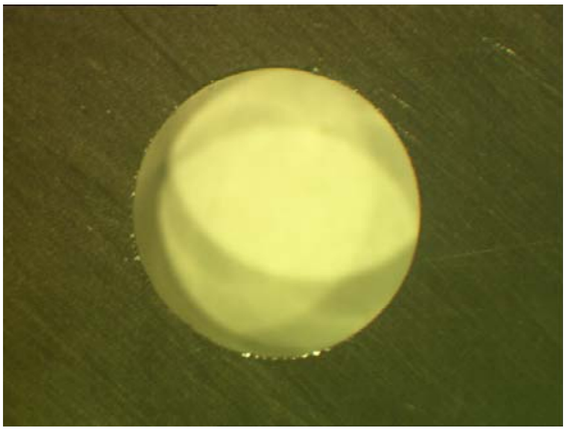


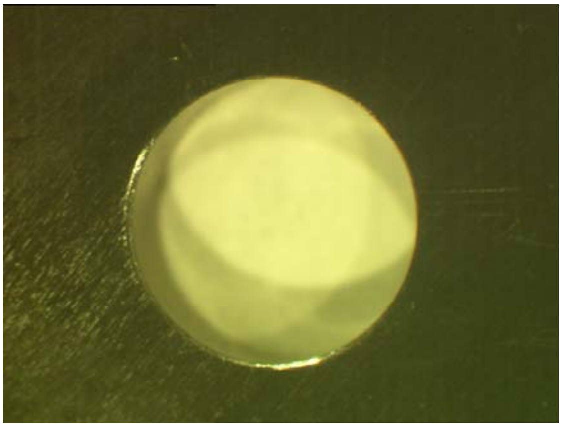
Figure 4.4 Hole position measurements for various drill types.

4.1.5. Drill life

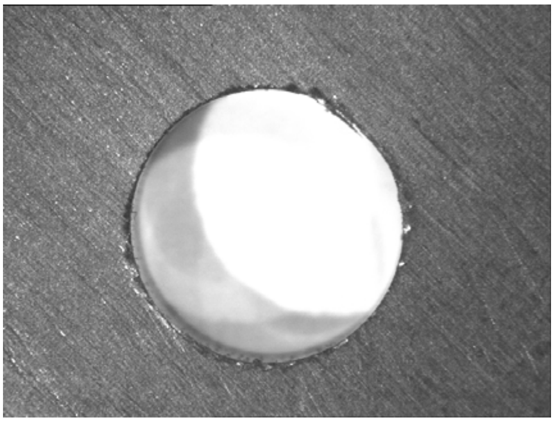
In the following Figure 4.5 optical micrographs of holes are shown for a single drill that was used to machine multiple holes successively.



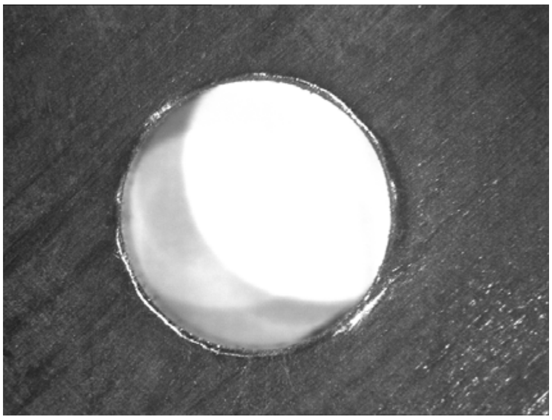
Ball Nose Drill Entry Hole 1 (∅ 6 mm)



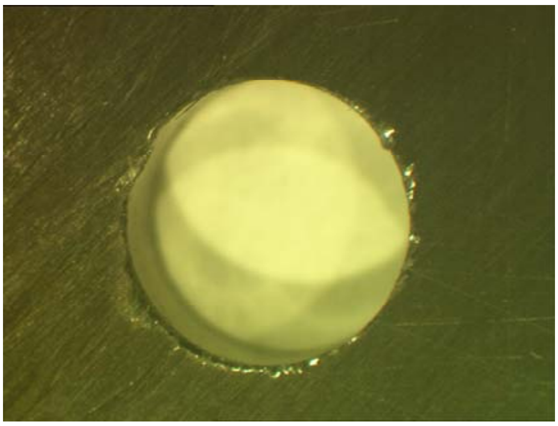
Ball Nose Drill Exit Hole 1 (∅ 6 mm)



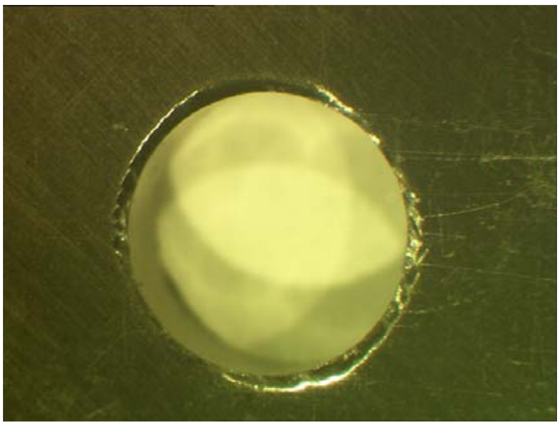
Ball Nose Drill Entry Hole 90 (∅ 6 mm)



Ball Nose Drill Exit Hole 90 (∅ 6 mm)

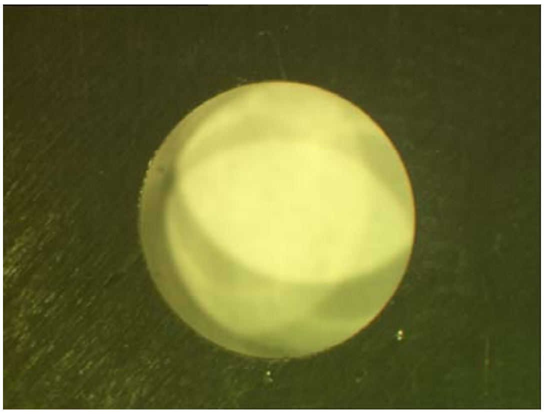


Ball Nose Drill Entry Hole 126 (∅ 6 mm)

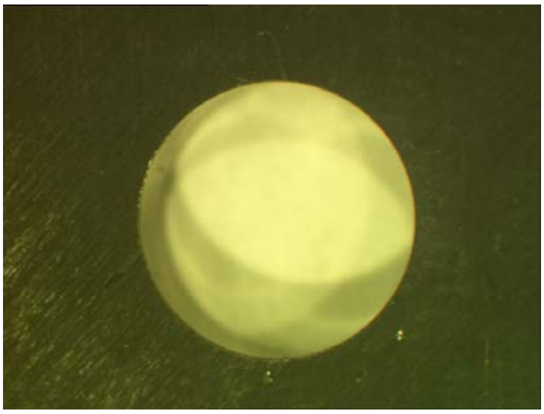


Ball Nose Drill Exit Hole 126 (∅ 6 mm)

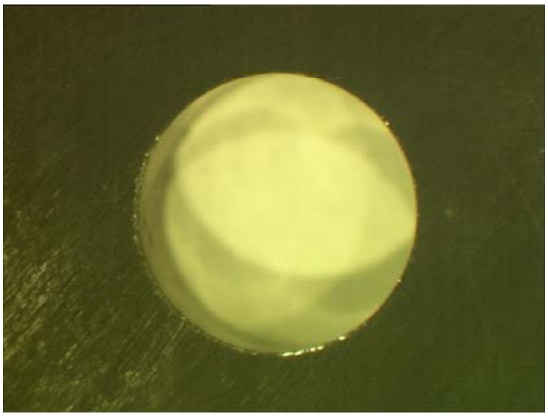
Figure 4.5a Hole quality obtainable from Ball nose drill



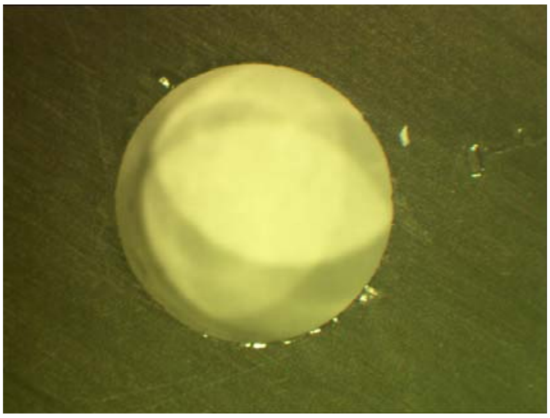
Dagger Drill Entry Hole 1 (∅ 6 mm)



Dagger Drill Exit Hole 1 (∅ 6 mm)



Dagger Drill Entry Hole 98 (∅ 6 mm)



Dagger Drill Exit Hole 98 (∅ 6 mm)

Figure 4.5b Hole quality obtainable from Dagger drill

4.2. Notching operations

Notching operations can be used for producing V notch, and waisted coupons (see bibliography for relevant test method).

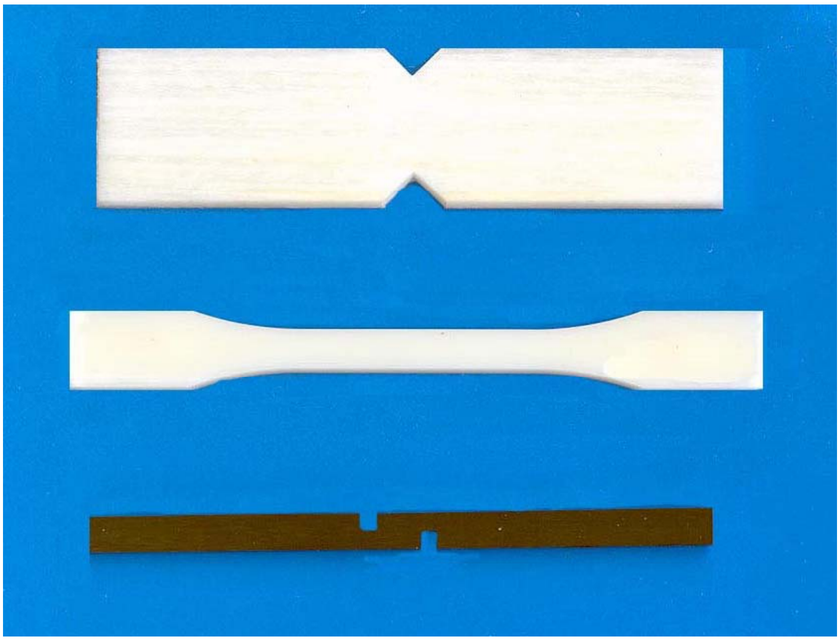


Figure 4.6 Example of notched/slotted and dumbbell coupons.

4.2.1. Machines

The machine shall be capable of achieving the required speeds and feeds quoted, suitable machines are:

- Circular saw/ diamond edge-grinding wheel.

4.2.2. Tool types

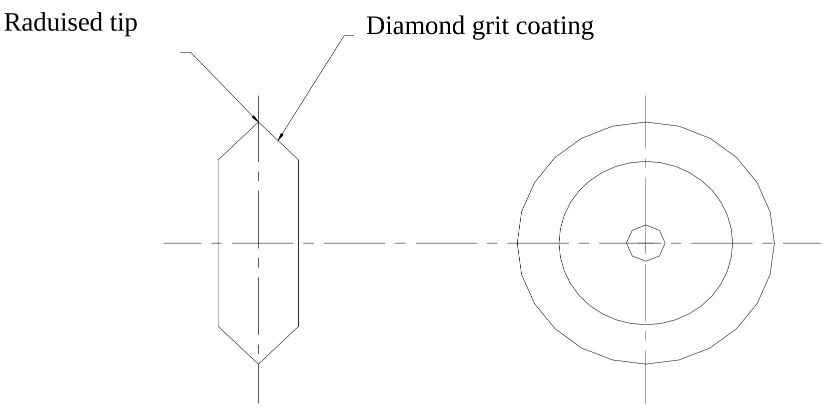


Figure 4.7 V Notch wheel

4.2.3. Operator experiences

Double V notch specimens were produced using both carbon and glass fibre/epoxy to investigate the use of the V notch cutting wheel.

When notching coupons using the V notch wheel or routing it is important that small finishing cuts are taken to allow the correct tolerances to be achieved, and that medium sized roughing cuts are taken to prevent a build up of heat on the tool, and prevent excessive wear.

Table 4.2 V Notch wheel cutting speeds and feeds.

Tool Type	Diameter (mm)	Material Thickness (mm)	Spindle Speed	Feed Rate
V notch	80	3-6	2000 rpm	Manual

It is possible to manufacture dumbbell or waisted coupons using the speeds and feeds given in Section 3 for a solid wheel but radiused to suit the coupon requirements (Figure 4.8).

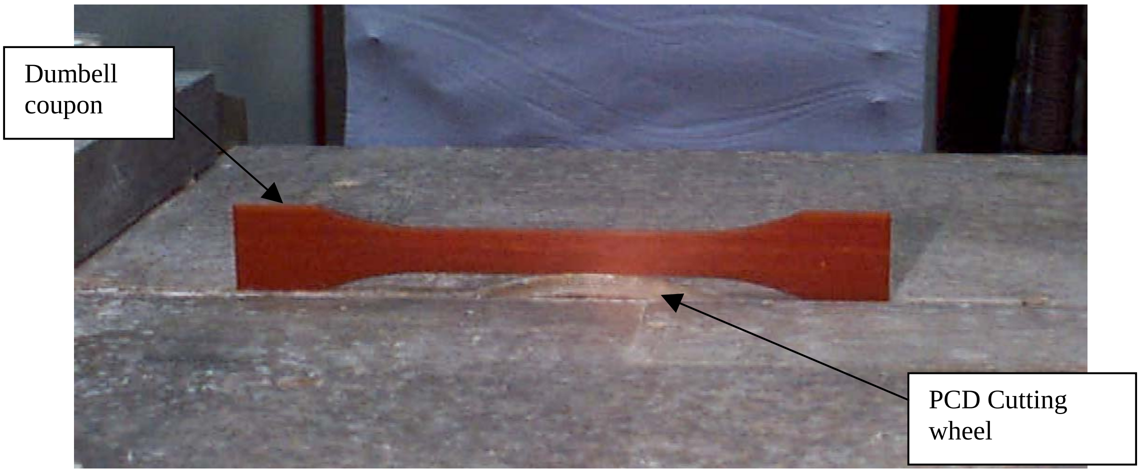


Figure 4.8 Machining of dumbell specimen

4.3. Routing operations

Routing operations can be used for the manufacture of rectangular coupons or waisted/ dumbell shaped coupons.

It is recommended that a 5% oil based coolant mixture be used.

Tooling should be checked for wear at regular intervals, as tool wear will cause delamination and poor quality edges.

The coupon should be held in a suitable jig to prevent movement of the coupon during machining (Figure 4.9).

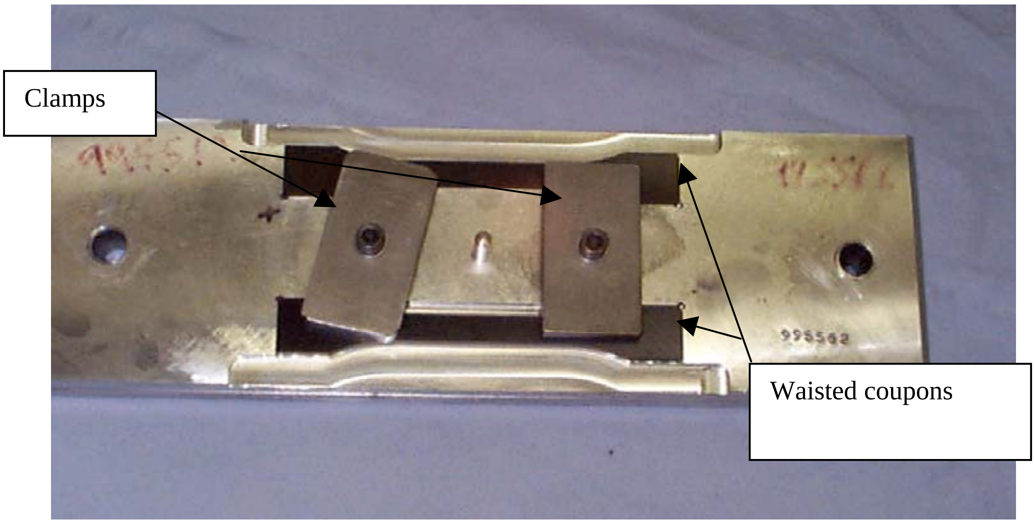


Figure 4.9 Dumbell machining jig

4.3.1. Machines

The machine shall be capable of achieving the required speeds and feeds quoted, suitable machines are:

- CNC Milling Machine

4.3.2. Tool types

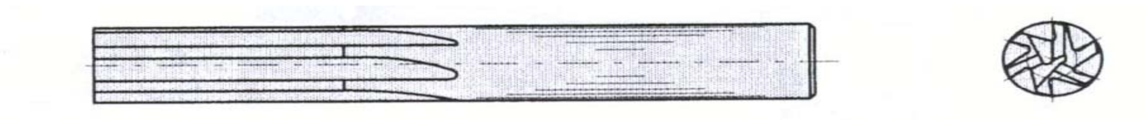


Figure 4.10 Six facet router

4.3.3. Operator experiences

The 6 Facet router performed well at 4000 rpm and 900 mm/min feed rate taking a full depth cut with 2 mm off the side on each pass on a 4 mm quasi-isotropic carbon/epoxy specimen. No delamination was seen on the finished coupons, using a faster spindle speed could see better results. Surface finishes of 0.7 μm Ra and 4.5 μm Rz were achieved. Table 4.3 details the manufacturers recommended speeds and feeds for this type of tool.

Table 4.3 Router cutting speeds and feeds

Tool Type	Diameter (mm)	Material Thickness (mm)	Spindle Speed	Feed Rate
Router	6.00	3-6	50-300 m/min	0.01-0.03 F/tooth

5. Selection of appropriate material and adhesive for end-tab bonding

The following stages should be considered when selecting an appropriate end-tab material and adhesive for bonding end-tabs to composite test coupons. All steps listed below should be assessed simultaneously to guarantee all considerations are included in the selection process.

The guidelines regarding the selection of adhesive should be read in conjunction with information provided by the adhesive manufacturer.

5.1. Ensure compatibility of adhesive with the composite and end-tab material to be tested

Initially, ensure that the adhesive class selected is chemically compatible with the composite material to be tested and end-tab material to be bonded. Also, ensure that the adhesive selected is thermally suited to the composite and end-tab materials used i.e. cure temperature is below the T_g of other materials used.

5.2. Define required adhesive performance

The failure load of the composite test coupon should be estimated, and converted to an adhesive shear strength requirement through knowledge of the total end-tab surface area. This average shear strength can then be defined as the minimum required performance for the adhesive.

The adhesive selected should be of a 'flexible' nature with an elongation at break greater than that of the material under test.

5.3. Environmental exposure requirements for adhesive and end-tab material

The temperature, humidity, duration and nature of any coupon exposures to aggressive environments post end-tab bonding must be taken into account. Information is required that demonstrates the end-tab adhesive maintains the required shear strength after the exposure is complete. Manufacturers may provide this information, or offer advice regarding the most appropriate adhesive for different conditions. It may be necessary to undertake adhesive lap shear testing using the appropriate environmental exposure conditions to obtain this information.

If using fibre-reinforced plastic end-tabs it should be recognised that moisture will also be absorbed by the end-tab during any subsequent environmental exposure of the bonded coupons. Care must be taken to ensure that the moisture uptake is not sufficient to degrade the end-tab performance to an extent where failure of the end-tab may occur. The use of aluminium end-tabs alleviates this potential problem but may not be possible due to other considerations.

6. Preparation of test coupons and end-tabs prior to bonding

The following section should be read in conjunction with the manufacturer's instructions regarding appropriate surface preparation for the adhesive being used. However, the following general statements apply:

The composite coupon and end-tab surfaces to be bonded must be suitably pre-treated. This will help ensure the success of the bonding operation and will also help attain maximum adhesive performance. For composite substrates, the preparation process should remove the surface film of matrix resin to expose reinforcing fibres. The preparation technique may take the form of vapour, sand or grit blasting, hand or mechanical abrasion, or for certain substrate materials (some thermoplastics) preparation including "corona discharge" may be required.

For all preparation methods care must be taken to pre-treat only the area to subsequently be bonded. This can be achieved by masking specimen regions likely to be affected by the preparation operation. Preparation extending into the coupons test gauge length may result in premature failure.

Independent of the method used, the surface of the substrates following pre-treatment should be free from oil, grease, dirt and all loose particulate contamination. This can be simply achieved by wiping the freshly abraded surface with a suitable solvent wipe. The visual appearance of the final pre-treated surface should be consistently dull, with no evidence of the original surface apparent. If a simple check of preparation quality is required a water-break test can be completed on the prepared surface.

6.1. Water break test method

This method covers the detection of the presence of hydrophobic (nonwetting) films on surfaces and the presence of hydrophobic organic materials in processing ambients. When properly conducted, the test will enable detection of molecular layers of hydrophobic organic contaminants. On very rough or porous surfaces the sensitivity of the test may be significantly decreased (See Bibliography for ASTM F22-65 standard details).

<u>Note:</u> *It is important that the application of adhesive and subsequent bonding is conducted as soon as possible after the preparation process is complete.*

7. Techniques for bonding end-tabs

Application of the adhesive to the end-tab and/or substrate material should be completed only after carefully reading the manufacturer's instructions. Particular attention should be paid to the application sequence for adhesive selected, whether adhesive should be applied to one or both surfaces and whether a priming layer of adhesive, or specific priming product, should first be applied. Also the recommended curing instructions should be carefully noted, including temperatures and pressures.

The adhesive should be applied covering the required surface(s) as noted above, paying particular attention to eliminating all entrapped air. On application of the end-tab to the substrate, light pressure should reveal adhesive spew at all edges of the coupon illustrating sufficient wetting. Ensure that this spew is not excessive and wipe away excess if necessary.

Whilst it is not possible to guarantee that adhesive has filled the gap in the central region of the end-tab, if the above guidelines have been followed this potential problem should be minimised.

7.1. Control of bondline thickness and fillets

In order to ensure uniformity of loading during subsequent testing it is desirable to produce a consistent thickness at all end-tab/substrate bondlines. This can be simply achieved with the use of adhesive films with a thin carrier. However if liquid or paste resins are used, products are available that can be mixed with the adhesive to control bondline thickness, e.g. glass microspheres. As a minimum control, the quantity of adhesive applied to each surface should be metered. If the production of an adhesive fillet is desired this should also be consistent across the width of the coupon to ensure uniformity of loading.

7.2. Curing

Coupon and end-tab assemblies can be cured using a variety of methods including simple ovens, autoclave vacuum bagged, pressclave or free standing room temperature cure for some systems. However, in all cases a method for maintaining the parallelism of end-tab and coupon surfaces should be employed.

7.2.1. Panels

If end-tab strips are to be bonded to a substrate laminate as indicated in procedure A, Figure 2.1, the following is recommended.

In order to ensure that the end-tab strips are correctly aligned, and accurately separated to the required coupon gauge length, it is recommended that spacers are manufactured and placed at opposite ends of the test plate whilst the bonding process is undertaken.

For adhesives other than film adhesives, it is likely that these spacers will interfere with the production of the bond fillet. Therefore, it is recommended that the spacers be removed during adhesive cure. Also, before removing the spacers, the end-tab strips should be secured with a suitable release tape that will not adhere to the finished end-tab/substrate assembly. This will ensure the end-tabs do not move during transport of the assembly for curing.

When adhesive film is employed the spacers can remain in place throughout the cure cycle due to reduced adhesive spew. Care should be taken to ensure the ends of the spacers are coated with release agent or similar to aid removal after cure.

7.2.2. Coupons

If coupons have been machined individually, and are to be end-tab bonded individually, as indicated in procedure B, Figure 2.1, then the following procedure is recommended.

Where possible alignment jigs should be used to ensure both the gauge length dimension is controlled and that the end-tab is aligned parallel to the coupon. An example fixture is illustrated in Figure 7.1.

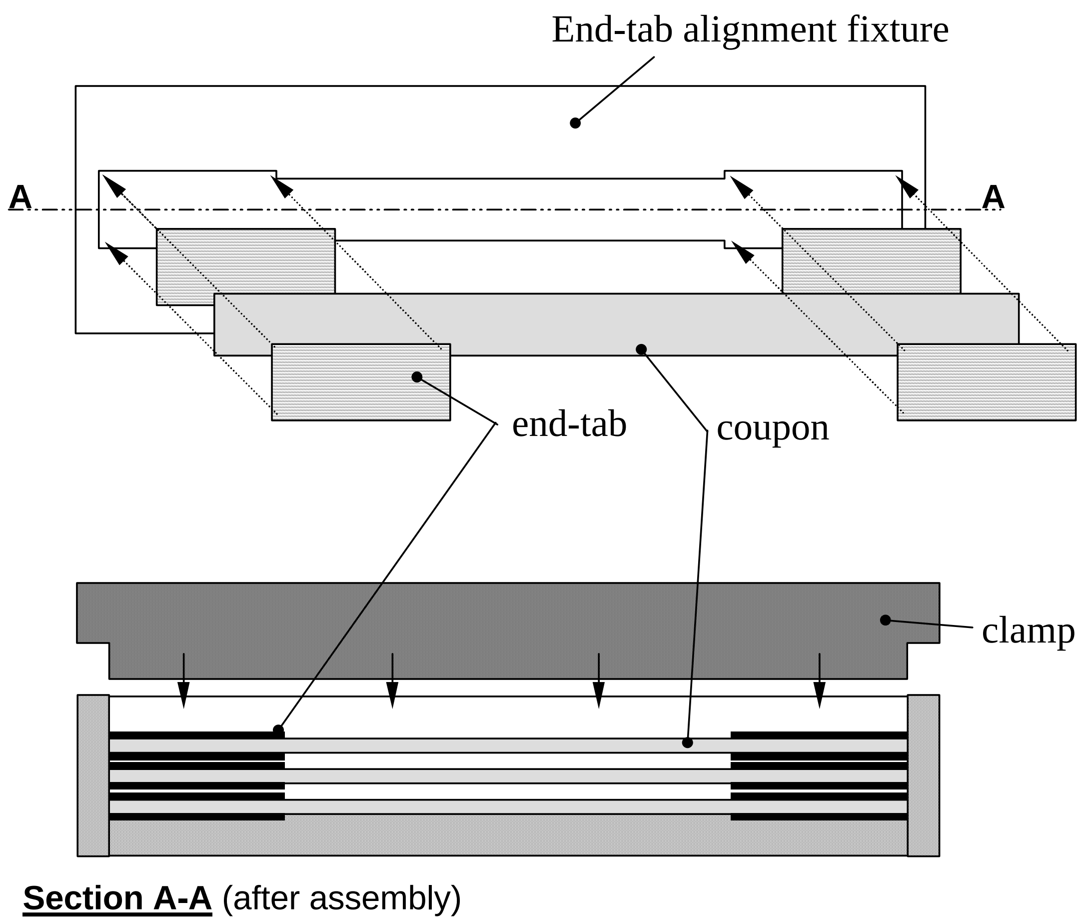


Figure 7.1 Plan view of alignment jig for end-tabbing test coupons

To use the alignment fixture two pre-treated end-tabs are dropped into the specifically sized slots. Next the coupon with adhesive applied to all four pre-treated surfaces is placed onto the end-tabs, followed by the two final pre-treated end-tabs. The whole assembly is then placed in the oven for cure with the mating clamp slotted in place to ensure the parallelism of the end-tabs and coupons. The jigs are designed to allow several coupons to be stacked during cure, although care must be taken to ensure adhesive escape does not lead to difficulty in removing cured coupons from the jig after cure. This can be controlled using a release film sheet between each stacked coupon. A separate jig will be required for each set of coupon gauge length, width and thickness dimensions.

8. Techniques for final coupon quality inspection

Various methods can be employed from the initial panel manufacture through to the finished coupon specimen to ascertain the quality of the individual specimens some of these are listed below.

8.1. Damage detection

8.1.1. C-scan

The ultrasonic c-scan technique is particularly useful for detecting and sizing potential coupon damage, such as delamination. A three part standard has been submitted to BSI, which is likely to appear as an Aerospace EN standard (see Bibliography).

The three parts are:

Part 1 – Operational procedure
Part 2 – Transducer calibration procedure
Part 3 – Preparation of reference defects and reference panels

8.1.2. X-ray

This technique is particularly useful for detecting damage at edges (e.g. drilled holes) when c-scan has poor resolution, and is also useful for detecting matrix cracking.

8.1.3. Hand magnifier / Optical (stereo) microscope

Used to check generally for damage, including burns on cut edges.

8.2. Surface & geometrical measurement

8.2.1. Talysurf

Used to measure the surface roughness. As well as metrology level equipment, relatively cheap hand held equipment are available with more than adequate resolution. (See data in Table 3.3, Section 3)

8.2.2. Micrometers, vernier callipers and setsquares

Used to check the overall dimensions, parallelism, hole positioning. Micrometers and verniers are available freely and with an adequate resolution within 0.01 mm and 0.05 mm respectively. Squares are used to check squarness of edges and faces. Normal engineering grade equipment is acceptable.

9. Industrial experiences

9.1. Machining questionnaire results

At the beginning of the programme a review on current practices in industry was conducted by means of a questionnaire this was sent to industrial partners regarding the manufacture of composite test specimens including drilling, slitting and end-tabbing operations is detailed below. The feedback from the questionnaire is given in the tables below.

Table 9.1 End-tabbing procedures

Site	Material	Surface Prep.	Adhesive
1	GFRP	Mech. Abrasion	--------
2	Tufnol	Mech. Abrasion 120 Grit	Araldite 403
3	Tufnol	Mech. Abrasion 120 Grit	Ecobond Adhesive
4	Composite	Vapour Blast (water/alumina)	Cytec proprietary adhesive
5	Aluminium	Mech. Abrasion 200 Grit	Epoxy EA9394 or Redux 322 film
6	GFRP/parent material	Peel ply	----------
7	Woven/GFRP	Peel Ply	Redux 319/322
8	Al/Comp.	Hand Abrasion 220 Grit	3M EM3960
9	Tufnol 10G/40	Light Mech. Abrasion	MA320
10	Tufnol	Mech. Abrasion	Araldite 2011

Table 9.2 Drilling procedures

Site	Drill Type	Drill Speed (rpm)	Drilling fluid	Notes
1	Klenk drill	400	YES	Backing material used
2	Diamond -Trepanne	2500	YES	-------
3	Cobalt steel brad and spur point	-----	NO	Backing material used
4	Tungsten Carbide	650	NO	Backing material used
5	Tungsten Carbide twist or fluted	3830	YES	Backing material used
6	Carbide tip/solid carbide	Various	YES	Backing material used
7	Tungsten Carbide	700	NO	Backing material used
8	Fluted Solid carbide twist drill	600	NO	Backing material used
9	6mm carbide slot drill	3000	YES	Backing material used, specimen drilled halfway through then turned over and drilled to prevent fibre breakout.
10	HSS twist drill	900	NO	Backing material used.

Table 9.3 Slitting procedures

Site	Cutting speed (rpm)	Feed rate (mm/min)	Cutting Fluid	Cutting Wheel
1	3600	400	5% oil based	Diamond blade
2	5000	600	Hysol/water	Diamond saw
3	3000	150	95% dilution semi-synthetic	7" Diamond saw
4	-----	-----	Sarelf SS	Circular
5	1500	1000	Cimcool/water	Diamond saw
6	500	500	Coolant	150mm dia. Diamond saw
7	------	-----	No	8" Carbide impregnated
8	2500	-----	------	Band saw
9	5000	600	5% Dromus cutting fluid	PCD 126 grit
10	5000	300	Ecocool CGF/water	Diamond saw 44/60 grit

9.2. Conclusions from the machining questionnaires

It is clear from the questionnaire responses that there is some degree of standardisation of practices. The following points were drawn.

1. For end-tabbing purposes all the participating partners used some form of end tab (usually GFRP / Tufnol). It can be seen from Table 9.1 that to be assured of a sufficiently strong end-tab/ substrate bond some form of mechanical abrasion of the substrate was used.

2. High shear strength adhesive was used to bond the tabs.

3. Although a range of drill speeds ranging from 400 rpm to 3800 rpm were employed, all of the participants used a specialist drill type both in term of design and material to achieve satisfactory results.

4. The majority of the participants used sacrificial material to prevent fibre breakout on the specimen back face when drilling.

5. Most of the participants used a circular saw with either diamond or carbide particles bonded to the cutting surface for slitting operations. Operating speeds ranged from 500 rpm to 5000 rpm, used mostly in conjunction with a cutting fluid.

10. Round-Robin experiences

During the course of the programme two Round-Robins were organised. The first to access the suitability of the techniques used by the participating industrial partners when asked to manufacture a number of test specimens from supplied composite plaques. The second Round-Robin was organised to demonstrate the usability of the compiled "Measurement Good Practice Guide". Comparing the results and feedback from the industrial partners allowed some conclusions to be drawn.

10.1. Round-Robin content

In the first Round-Robin three specimen types were sent to the industrial partners: unidirectional tensile, unidirectional compression specimens and pin bearing. In addition to the specimens, various questionnaires were circulated to ascertain the current machining practices of the participating industrial partners. The information gathered from these questionnaires was tabulated and plotted to aid comparison.

10.2. First Round-Robin results

The first Round-Robin was conducted with participation from following companies:

BAE SYSTEMS (Walton)
Cytec
DERA
GKN
Hexcel Composites Ltd
McLaren
National Physical Laboratory
Roll Royce Plc

For the tension and compression tests a typical brittle resin/ intermediate carbon fibre system was used. For the pin-bearing test, the first Round-Robin used a fabric reinforced tough epoxy/ high strength carbon fibre system. This was replaced by the brittle resin system in a quasi-isotropic lay-up for the second Round-Robin as being more demanding.

10.2.1. Compression tests

The compression tests were carried out using a shear loaded IITRI (Illinois Institute of Technology Research Institute) compression rig at a rate of 1 mm/min according to BS EN ISO 14126**.** The results are shown below in Table 10.1 and Figure 10.1. In general the following points were found:

- Higher failure stresses were obtained with a specimen that was tight fitting in the test fixture.

- All of the failures were within the end-tab region of the compression specimens.
- End tab alignment was crucial to achieving a tight fit within the test fixture.
- Squareness of the specimen ends was necessary to stop shear failures within the end tab region.

Table 10.1 First Round-Robin compressive results (MPa)

Specimen	Site 1	Site 2	Site 5
1	1241.6	1124.7	1069.4
2	1158.1	1046.2	1089.6
3	1206.4	1135.9	1310.2
4	1285.2	1178.1	1061.5
5	1270.0	1004.2	-------
Mean	**1232.3**	**1097.82**	**1222.8**
Standard dev.	**51.2**	**70.79**	**118.9**
CoV	**4.2**	**6.4**	**9.7**

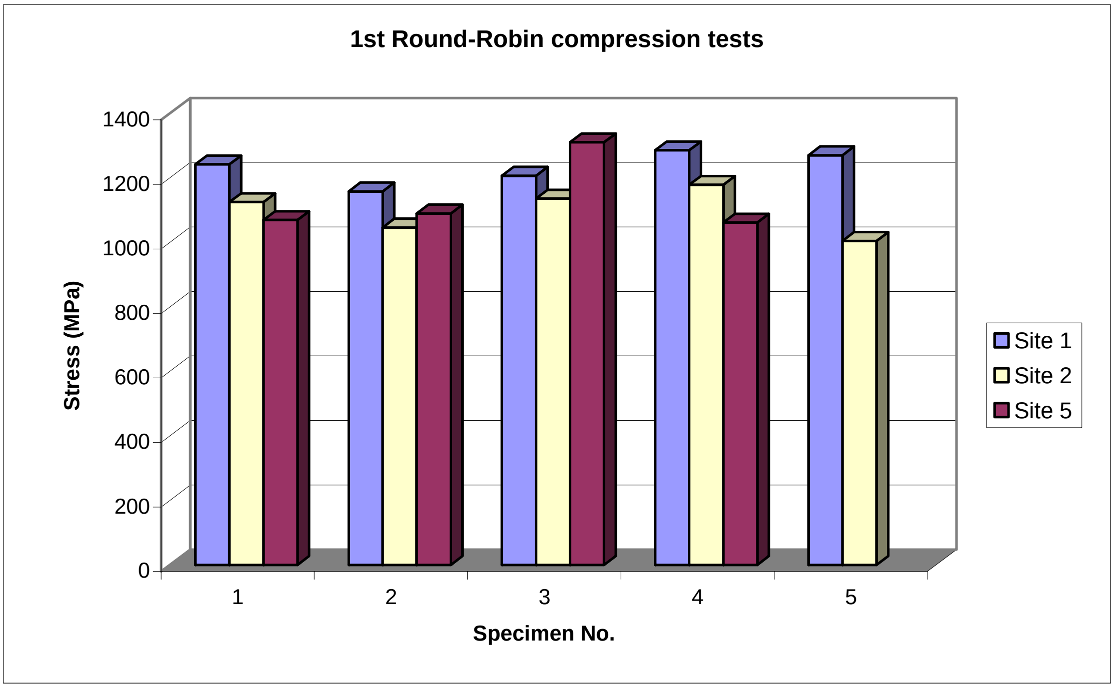


Figure 10.1 Comparison of compressive strength results

10.2.2. Tensile tests

The tensile tests were carried out according to BS EN ISO 527. The results are shown in Table 10.2 and Figure 10.2.

Due to the catastrophic nature of the unidirectional tensile test it was difficult to ascertain any particular reason for the variation in the specimen results, other than that of the usual scatter associated with the mechanical testing of composite specimens. It was noted that all of the end tabs stayed intact and no slippage of the end-tabs or grips had occurred.

Table 10.2 First Round-Robin tensile results (MPa)

Specimen	Site 1	Site 2	Site 5
1	2406.8	2377.2	2306.2
2	2046.9	2456.9	2398.8
3	2061.1	2318.4	2311.8
4	2159.3	2278.4	2336.4
5	2151.2	2116.9	2402.5
Mean	**2165.1**	**2309.6**	**2351.1**
Standard dev.	**144.4**	**126.9**	**81.5**
CoV	**6.7**	**5.5**	**3.5**

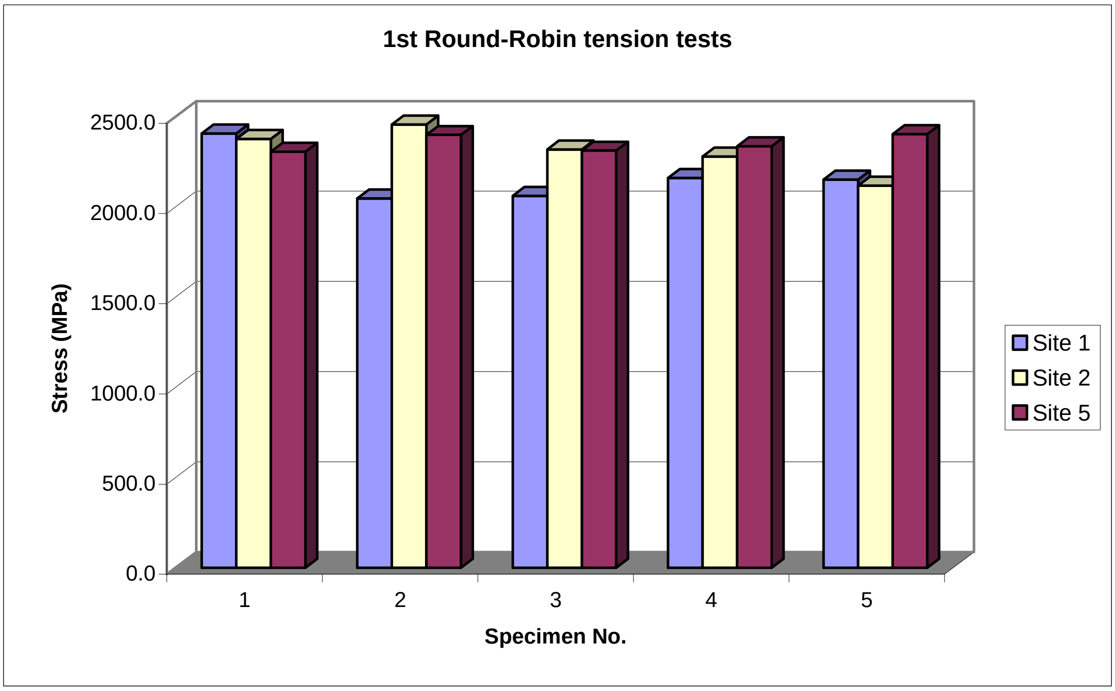


Figure 10.2 Comparison of tensile results

10.2.3. Pin Bearing tests

The pin bearing tests were conducted according to ISO NWI 714. Table 10.3 details the results. Included in the Table are failure load, bearing strength and the measured distance of the hole from the measured centreline of the specimen. Figure 10.3 shows the effect of hole distance from the specimen centreline on the measured pin bearing strength. For one set of specimens the hole was positioned randomly along the specimens axis and was up to 18 mm from the required position.

Table 10.3 Pin Bearing results from the first Round-Robin

Predicted Centre (mm)	Off Centre (mm)	Failure Load (kN)	Failure disp. (mm)	Pin bearing strength (MPa)	Specimen Number
Site 1a (Pillar Drill)					
17.91	0.22	10.44	0.5904	439.5	QFF001
18.04	-0.13	10.26	0.5243	423.8	QFF002
18.08	-0.08	10.59	0.5344	434.4	QFF003
18.03	-0.42	10.86	0.5403	449.0	QFF004
17.87	0.13	10.55	0.5735	440.9	QFF005
Average (MPa) 473.5 Std.dev 9.3, CoV 2%					
Site 1b (CNC Milling machine)					
17.92	-0.03	10.12	0.5722	417.3	QFF009
18.10	-0.03	10.22	0.5258	422.8	QFF010
18.07	0.01	9.79	0.5209	402.4	QFF011
17.97	0.00	9.99	0.5618	410.5	QFF012
Average (MPa) 413.5 Std.dev 7.6, CoV 1.8%					
Site 2					
17.93	-0.06	10.44	0.5763	432.0	QFF038
17.91	-0.29	9.96	0.5498	413.2	QFF039
17.94	-0.14	9.8	0.5271	404.2	QFF040
17.83	-0.42	10.53	0.5945	432.7	QFF041
Average (MPa) 420.5 Std.dev 12.5, CoV 3%					
Site 5					
17.95	0.14	10.02	0.5356	417.5	QFF017
17.91	0.45	10.06	0.5387	418.0	QFF018
17.94	0.11	9.6	0.5595	395.3	QFF019
17.90	0.20	10.25	0.5594	423.7	QFF020
Average (MPa) 416.3 Std.dev 12.4, CoV 3%					
Site 7					
17.97	-0.05	10.33	0.5682	424.9	QFF031
17.94	-0.05	10.43	0.591	434.1	QFF032
17.91	-0.03	10.73	0.5802	447.9	QFF033
17.92	-0.02	10.75	0.5956	448.6	QFF034
Average (MPa) 437.4 Std.dev 10.5, CoV 2.4%					
Site 8					
17.78	-0.92	9.98	0.6019	409.0	QFF024
17.94	-0.74	9.76	0.6841	403.4	QFF025
17.93	-0.33	9.9	0.5799	409.7	QFF026
18.14	-1.15	9.77	0.6736	408.1	QFF027
Average (MPa) 409.2 Std.dev 4.4, CoV 1.1%					

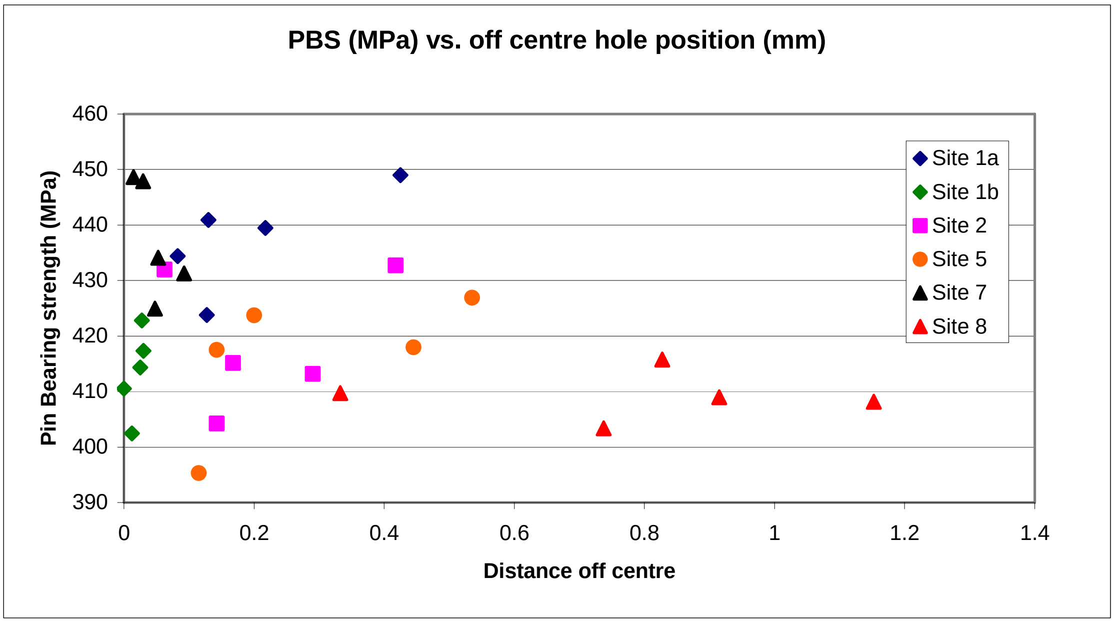


Figure 10.3 Pin bearing strength vs. off centre hole position.

10.2.4. Conclusions from first Round-Robin

A degree of standardised machining procedures could be seen from the replies to the machining questionnaires. Each partner, although somewhat limited by their available machining equipment, had knowledge of how to machine mechanical testing coupons.

As can be seen from Figures 10.1 and 10.2 the variation in actual mechanical strength data for the unidirectional specimens was reasonable and did not seem to be dependant on machining route.

Figure 10.3 shows the pin bearing results. As previously the spread of data is not large and although there is some variation in drill type and speed (and therefore likely hole quality) this does not seem to have affected the results greatly. Figure 10.3 shows that there is not a clear correlation between off centre drilling of the pin holes and pin bearing strength.

10.3. Second Round-Robin

The second Round-Robin conducted was identical in content to the first. However, Imperial College, London and Warwick Manufacturing Group also participated in the study.

10.4. Mechanical test results

The mechanical testing results for the unidirectional tension, compression and pin bearing specimens are given in sections 10.4.1 and 10.4.2.

10.4.1. Compression tests

Table 10.4 Second Round-Robin compressive results (MPa)

Specimen	Site 1	Site 2	Site 5	Site 9
1	1606.6	1729.9	1091.1	1584.8
2	1575.5	1475.2	1537.3	1573.7
3	1493.8	1717.5	1615.5	1474.2
4	1590.5	1720.8	---------	1473.9
5	1663.7	1744.2	--------	1320.7
Mean	**1586.0**	**1677.5**	**1414.6**	**1485.5**
Std dev.	**61.4**	**113.6**	**282.9**	**106.1**
CoV	**3.9**	**6.8**	**20.0**	**7.1**

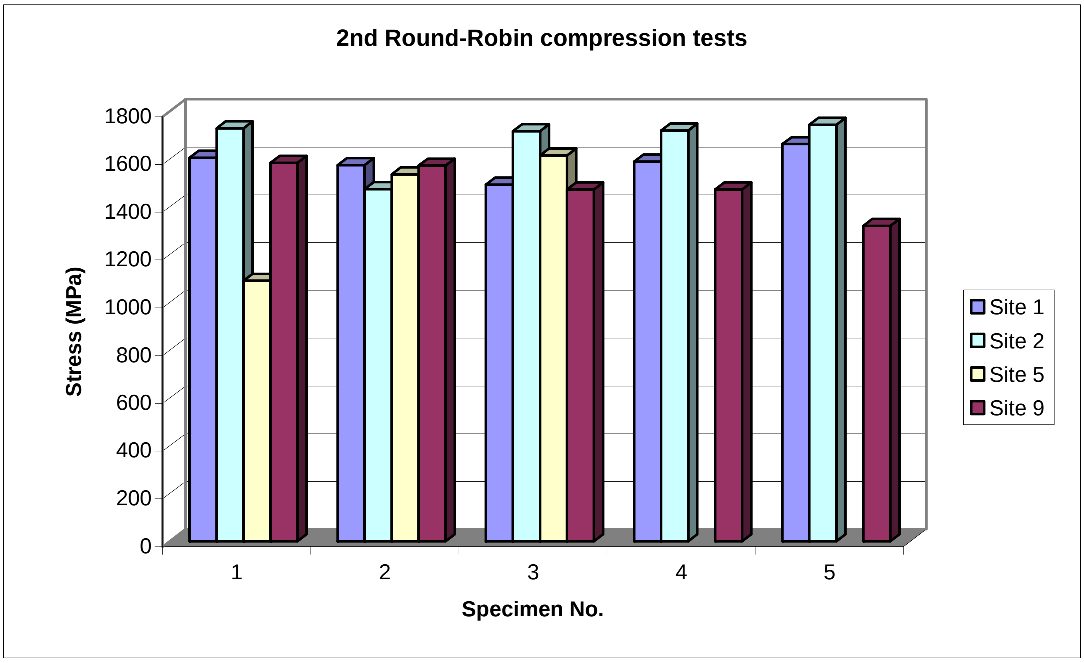


Figure 10.4 Comparison of Compressive Results

10.4.2. Tensile tests

Table 10.5 Second Round-Robin tensile results

Specimen	Site 1	Site 5	Site 9	Site 10
1	2347.6	2167.6	1032.1	2585.0
2	2236.8	2175.4	1243.7	2169.0
3	2145.3	2099.7	1079.1	2288.0
4	2262.7	2241.0	1124.3	2243.2
5	2136.3	2314.9	1099.6	2592.5
Mean	**2225.7**	**2199.7**	**1118.3**	**2375.5**
Std dev.	**87.8**	**81.5**	**111.1**	**199.2**
CoV	**3.9**	**3.7**	**9.9**	**8.4**

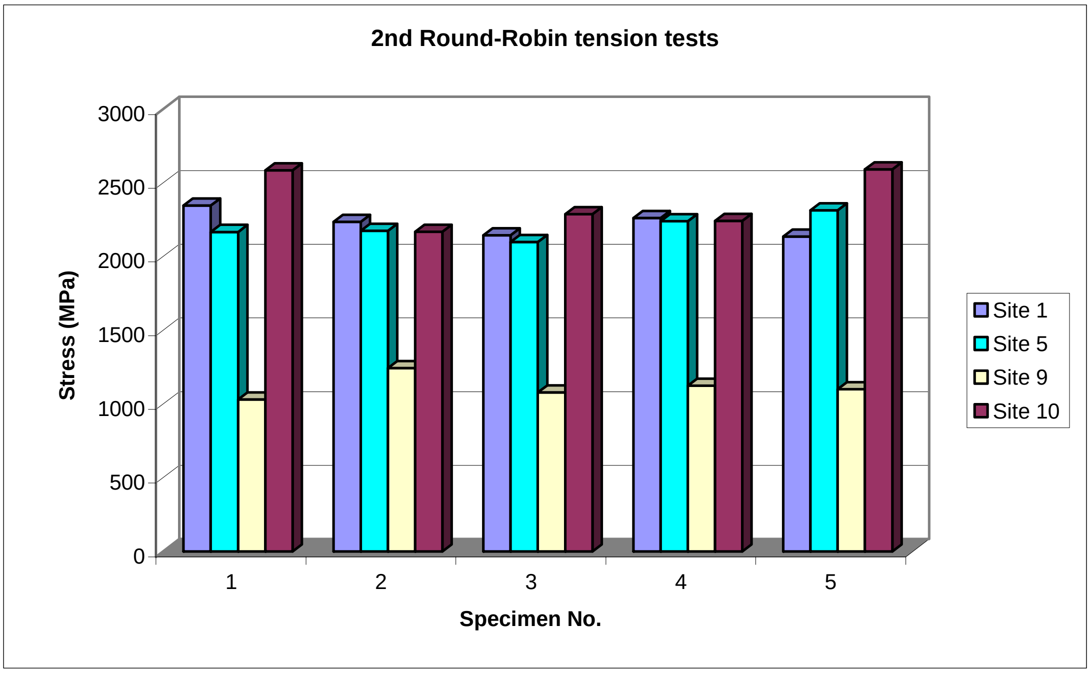


Figure 10.5 Comparison of Tensile Results

10.4.3 Pin Bearing tests

Table 10.6 Second Round-Robin Pin Bearing results (MPa)

Predicted Centre (mm)	Off Centre (mm)	Failure Load (kN)	Failure disp. (mm)	Pin bearing strength (MPa)	Specimen Number
Site 1					
18.05	-0.14	16.31	0.7528	672.2	QSB001
18.01	-0.15	16.93	0.7712	704.5	QSB002
18.04	0.07	17.6	0.7841	725.6	QSB003
18.04	0.10	17.76	0.795	739.0	QSB004
18.02	0.09	17.8	0.8117	727.8	QSB005
18.03	0.07	17.34	0.7731	720.2	QSB006
Average (MPa) 714.9 Std.dev. 23.8, CoV 3.3%					
Site 5					
18.22	-0.35	15.77	0.7129	649.0	QSB013
18.46	-0.29	15.55	0.7711	663.0	QSB014
18.48	0.17	15.38	0.6778	638.1	QSB015
18.44	0.32	16.49	0.7336	688.0	QSB016
18.69	-0.20	15.64	0.7011	651.0	QSB017
18.29	-0.03	15.8	0.7112	651.0	QSB018
Average (MPa) 656.6 Std.dev. 17.3, CoV 2.6%					
Site 9					
18.01	-0.02	15.4	0.6866	639.3	QSB007
18.01	-0.05	16.95	0.7639	708.2	QSB008
18.01	-0.03	16.89	0.7432	701.4	QSB009
18.03	-0.03	17.01	0.7537	705.0	QSB010
18.10	-0.05	14.2	0.7047	612.0	QSB011
18.03	-0.07	17.57	0.7828	736.0	QSB012
Average (MPa) 683.6 Std.dev. 47.4, CoV 6.9%					

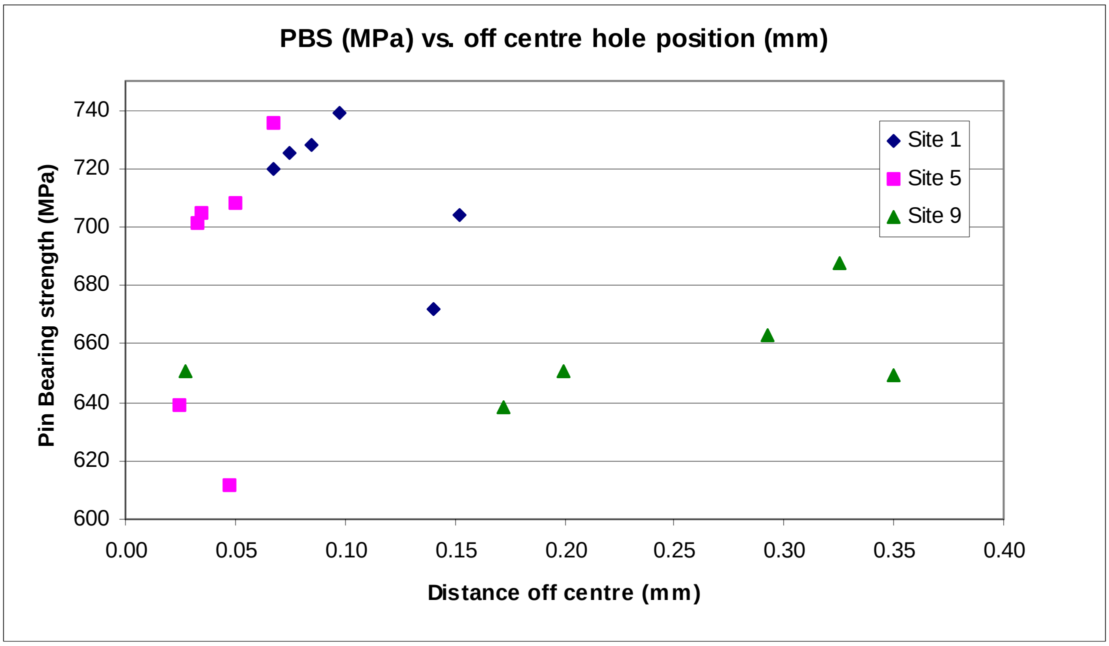


Figure 10.6 Pin Bearing Strength vs. Off Centre Hole Position

10.4.4 Conclusions from 2nd Round-Robin

As seen in the first Round-Robin, the machining route chosen by the industrial partners did not generally affect the mechanical testing data. However, failure of the end tab adhesive resulted in unacceptable test results for one of the partners.

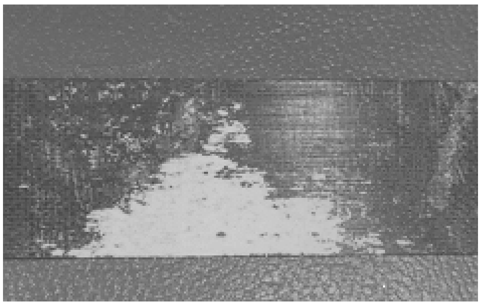


Figure 10.7 End-tab adhesive failure

From the first Round-Robin, the variation of pin bearing strength vs. hole misalignment was seen to be minimal. Values were slightly higher than for the first Round-Robin series of test as a different materials was used. For one set of specimens the incorrect hole size was machined, although in the right position, and these specimens could not be tested.

10.5. Round-Robin Overall conclusions

In general the following points were drawn from the two Round-Robins:

1. Machining route has little affect on the overall strength of the specimens tested within the Round-Robin, partly due to the degree of standardisation in practices already in place in the industry.

2. Some anomalies in the results throughout the two rounds of testing were seen. These were attributed in the main to inaccuracies in specimen size rather than machining route or quality.

3. The pin bearing strength of the specimens is not greatly affected by the detailed accuracy of the hole position. However, it is important that the correct sized hole is drilled in the correct position.

4. Selection of appropriate adhesive type appears to still be an issue as demonstrated in the tab failures of one of the partners. The draft has therefore been strengthened in this respect in an attempt to prevent such events.

5. It appears that the most significant effects on mechanical property data have been as a result of machining and ancillary errors (specimen size, hole position and adhesive selected) and due to poor machining quality or incorrect approach. Hence, the draft for standardisation pays attention wherever possible to preventing mistakes in processes ancillary to the main procedure itself.

Annex 1. Typical fibre reinforced composite material types, process routes & machining characteristics

Process/Manufacturing route	Resin type	Fibre type	Typical Vf (%)	Typical material	Typical product	Material machining characteristics
Injection moulded ISO 293-295	T/S	GF, CF	10-30	GF/ nylon	Consumer goods Automotive parts	Tendency to delaminate: low Suitable for cutting process, also grinding
Injection moulded ISO 1268-10	T/P	GF	10-20	Short fibre - thermosets	Electrical parts	Tendency to delaminate: low Suitable for grinding process
Press moulded (thermoformed) ISO 1268-9	T/P	GF, CF	20-40	GF/ PP (GMT)	Vehicle bulkheads and plates	Tendency to delaminate: low Suitable for grinding process, also cutting
Hand lay up/ spray lay up/ wet press ISO 1268-2/3	T/S	GF, CF	20-40	CSM/ polyester	General GRP products / boats	Tendency to delaminate: high Suitable for grinding process
Hot press moulded ISO 1268-8	T/S + filler	GF	15-30	GF/ polyester/ Filler (SMC)	Transport trim plates Electrical switch boxes	Tendency to delaminate: low Suitable for grinding process
Pultrusion ISO1268-6	T/S, T/P	GF	20-50	GF/ polyester mixed fibre format	Pultruded profiles walkways, ladders, civil constructions	Tendency to delaminate: medium Suitable for grinding process
RTM ISO 1268-7	T/S	GF, CF, (AF)	40-60	GF fabric/ epoxy	General high performance products	Tendency to delaminate: medium Suitable for grinding process
Filament wound ISO 1268-5	T/S, T/P	GF, CF, (AF)	50-70	GF / epoxy	Pipes, flywheels, cylinders and rings	Tendency to delaminate: high-medium Suitable for grinding process
Autoclave/ press etc (RFI) ISO 1268-4	T/S, T/P	GF, CF, (AF)	50-70	CF UD/ epoxy	Aerospace / grand prix	Tendency to delaminate: high-medium Suitable for grinding process

Index code:

T/S = Thermosetting
T/P = Thermoplastic
CSM = Chopped strand mat
UD = Uni-directional
AF = Aramide fibre
GF = Glass fibre
CF = Carbon fibre
GRP = Glass reinforced plastic
PP = Polypropylene
RFI = Resin Film Infusion
Vf = Volume fraction
RTM = Resin Transfer Moulding
SMC = Sheet Moulding Compound
GMT = Glass Mat Thermoplastic

Annex 2. Selection of machining tool type

Operation	Laminate type	Machine type	Tool type
Slitting	Themosets and thermoplastics with medium to high content of glass or carbon fibres	Slitting Saw	Solid PCD
			Slotted PCD
	Themosets and thermoplastics with medium to high content of aramid fibres	Slitting Saw	Serrated PCD
			Solid PCD
	Thermoplastics with medium to high content of matrix	Slitting Saw	High speed steel
			Solid PCD
Drilling	Themosets and thermoplastics with medium to high content of glass or carbon fibres	Pillar drill	Klenk
		CNC milling	Ball nose
			Dagger
	Themosets and thermoplastics with medium to high content of aramid fibres	Pillar drill	Klenk
	Thermoplastics with medium to high content of matrix	Pillar drill	Klenk
			HSS
		CNC milling	Ball nose
			Dagger
Routing	Themosets and thermoplastics with medium to high content of glass or carbon fibres	CNC milling	6 Facet router
	Themosets and thermoplastics with medium to high content of aramid fibres	CNC milling	6 Facet router
	Thermoplastics with medium to high content of matrix	CNC milling	6 Facet router
Notching	Themosets and thermoplastics with medium to high content of glass or carbon fibres.	Slitting Saw	V notch PCD
		CNC milling	6 Facet router
	Themosets and thermoplastics with medium to high content of aramid fibres	Slitting Saw	V notch PCD
		CNC milling	6 Facet router
	Thermoplastics with medium to high content of matrix	Slitting Saw	V notch PCD
		CNC milling	6 Facet router

HSS = High Speed Steel PCD = Poly Crystalline Diamond

Annex 3. Draft for standardisation

1. Scope

This Draft establishes the general principles and procedures to be followed when preparing test coupons from fibre reinforced plastic composites test plates or from finished products. It covers machining, surface preparation and end-tab bonding operations.

In order to establish a basis for preparation of reproducible and acceptable quality coupons the general procedures described shall be used. The exact procedures used will be selected or specified in conjunction with the relevant material specification and/or by the relevant standard test method. If sufficiently detailed procedures are not thus specified, it is essential that the interested parties agree on the preparation conditions to be used.

The following types of test coupons can be prepared:
- Rectangular coupons, with and without end-tabs.
- Machined coupons, as above, containing holes or notches.
- Dumbell coupons, plain.

The text applies to all types of reinforced thermo sets and thermoplastics, as appropriate.

2. Normative references

The following standards contain provisions, that, through reference in this text constitute provisions of this Draft. All standards are subject to revision, and parties to agreements based on this Draft are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid standards.

ISO 1268 -1 Fibre reinforced plastics – Test plates manufacturing methods:
Part 1: General conditions
Part 2: Contact and spray-up moulding
Part 3: Wet compression moulding
Part 4: Moulding of preimpregnates
Part 5: Filament winding
Part 6: Pultrusion moulding
Part 7: Resin transfer moulding
Part 8: Moulding of SMC, BMC
Part 9: Moulding of (GMT) glass mat thermoplastics

ISO 2818 Plastics – Preparation of test coupons by machining

3. Definitions

For the purposes of this Draft, the following definitions apply:

Feed rate, the traverse rate in mm/min between the cutting tool and the sample.

Spindle speed, the rotation rate at which the tool moves in revolutions/minute (rpm).

Cutting speed, the speed at which material is removed in m/min.

Note: To convert m/min to rpm the following formula may be used

$$N = \frac{1000\,V}{\pi\,D}$$

Where N = Spindle speed, rpm
V = Cutting speed, m/min
D = Diameter of the cutter, mm

4. Principles

This Draft specifies the machining and bonding procedures that enables samples of fibre reinforced plastic composites to be prepared as acceptable test coupons, in agreement with the requirement defined in the relevant test method. The material sample may be available as a test plate(s) or cut from suitable areas of a final product.

For coupons requiring end-tabbing, three procedures are available, as follows:

Procedure A End-tabbing (nb. excluding metal end-tabs) is applied to a test plate, or a section cut from it, prior to machining into separate coupons.

Procedure B Individual coupons are machined and then individually tabbed.

Procedure C Untabbed, or loose tabbed, coupons.

The exact shape dimensions and tolerances of the test coupons shall conform to the standard for the particular test method in question.

For fibre-reinforced plastics with a low fibre content the techniques in ISO 2818 should also be consulted.

5. Apparatus

5.1. Slitting or sawing machines

These may be used to prepare rectangular coupon coupons. They can be equipped with a circular saw or cutting disk. The machine shall be suitable for use with a coolant/lubricating fluid when using a cutting disk.

5.2. Slitting wheels

Shall be constructed with either high-speed steel or polycrystalline diamond (PCD) surface depending on material to be cut.

5.3. Drilling machines

These may be used to produce holes in the coupons. The machine shall be suitable for use with a coolant/lubricating fluid when in use.

5.4. Drills

Specialised drills are required for cutting composite materials. Several designs are currently available.

5.5. Milling machines

These may be used to prepare rectangular coupon coupons, dumbbell coupons, and to produce slots and holes. They can be equipped with either a drill or a routing tool bit. The machine shall be suitable for use with a coolant/lubricating fluid when in use.

5.6. Milling cutters

Specialised cutters are required for cutting composite materials.

5.7. Other machining methods

5.7.1. Water jet machines

High-pressure water jet (~ 2750 bar) used for machining a variety of different materials including composite materials. Abrasive such as garnet can be added to the water jet to increase the cutting efficiency. The cutting jet is usually mounted on a multiple axis manipulator system.

5.7.2. Laser

Commonly used lasers are neodymium/YAG and carbon dioxide, lasers "machine" composite materials by vaporisation. As above the cutting head is usually mounted on a system that allows a large degree of freedom of movement, hence intricate designs are possible.

5.7.3. Electrical discharge machining – EDM

Can be used as a method for machining conductive materials. The material to be machined is placed in a dielectric solution and submitted to a series of electrical sparks, that vaporises the material.

5.8. Adhesives

A suitable adhesive must be selected for bonding end-tabs securely to test coupons. The adhesive should be chosen to ensure the bond meets thermal, mechanical and chemical performance requirements.

5.9. Bonding ancillary equipment

5.9.1. Surface preparation

A technique of preparing the coupon and end tab surfaces is required to ensure adequate bond strength is achieved e.g. grit or vapour blasting, hand abrasion, etc.

5.9.2. Cleaning fluids

Appropriate cleaning fluids are required to degrease prepared surfaces before adhesive application.

5.9.3. Alignment and clamping fixtures

Fixtures should be used wherever possible to ensure parallelism of end-tab and coupon and to maintain required test gauge lengths. Clamping fixtures should also be used to achieve constant bondline.

5.9.4. Curing oven

Where required, a calibrated oven capable of achieving and maintaining the adhesive cure temperature should be used.

5.10. Tab materials

Glass fibre reinforced plastic laminates containing a square weave woven fabric or 0°/90° cross-plies set at 45° to the coupon axis are recommended. Other materials can be used for particular circumstances as noted in the test method standard. Alternate tabbing material, tabs made from material under test, mechanically fastened tabs, unbonded tabs or friction materials (emery paper, grit paper or fine finish grip faces) shall be shown to give a least equal strength values and no greater coefficient of variation (see ISO 527-5, clause 10.5) than the recommended tab material before use.

6. Procedure

6.1. Specimen preparation - general

The test coupons shall be machined from plates made according to ISO 1268 or by agreed alternative methods, or cut from suitable areas of final products. Due to the anisotropy of most fibre reinforced plastic composites the position and direction of the cutting of coupons must be recorded on a cutting plan according to the "zero degree" direction marked on the test plate, or by a defined direction in a final product.

Note: *A scheme is given in Annex A of ISO 1268-1 for indicating the direction and stacking sequence of lay-ups in laminated materials, and for marking the "zero degree" direction.*

Confirm, or determine, the type of composite material under consideration according to Annex 1.

Record the quality and manufacturing conditions of the supplied material.

Determine the required coupon sizes, number of coupons, tolerances, etc. as defined in the appropriate test method standard (see Bibliography for some relevant ISO test method standards).

Determine if procedure A or B is required for the addition of end-tabs from the appropriate test method standard (see Figure 1). Use procedure C for untabbed or loose tabbed coupons.

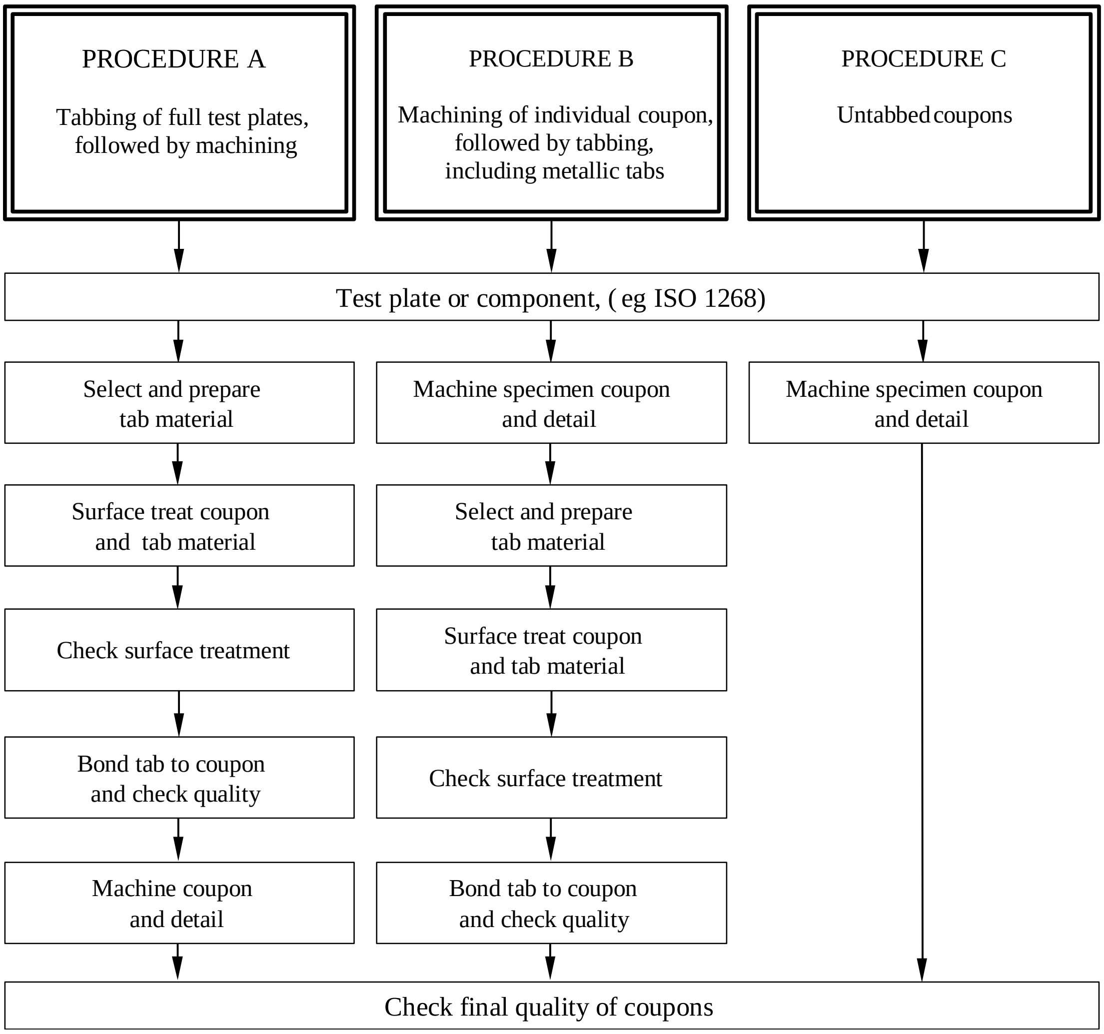


Figure A3.1 Alternative routes for coupon preparation

Note: For metallic end-tabs, Procedure B is used to avoid machining metal and composite at the same time.

6.2. Coupon preparation - Procedure A

Select the bonding tab material, adhesive and surface preparation applicable depending on the test conditions (e.g. test temperature, environmental conditioning) according to Annex 3 Section 5.

Machine tab material strips sufficient to bond across the width of the sample test plate, in accordance with the relevant test method.

Prepare and check the surfaces of the test material and end-tab material in the area to be bonded according to Annex 3 Section 5.

In conjunction with the adhesive manufacturers instructions and Annex 3 Section 5, apply and cure the adhesive.

Assess the quality of the tabbed plate.

Before machining into individual coupons, select the appropriate machining conditions according to Annex 3 Section 5 and any material specification instructions for the material in use. Using the detailed instructions in Sections 3 and 4 then machine the individual coupon blanks and details (eg holes, notches), respectively.

Assess the quality of the machined coupon according to Annex 3 Section 7.

6.3. Coupon preparation - Procedure B

Before machining into individual coupons, select the appropriate machining conditions according to Annex 2 and any material specification instructions for the material in use. Using the detailed instructions in Section 3 and 4 then machine the individual coupon blanks and details (e.g. holes, notches), respectively.

Select the bonding tab material, adhesive and surface preparation applicable depending on the test conditions (e.g. test temperature), including environmental conditioning, according to Section 6.

Machine tab material strips sufficient to bond across the width of the sample test plate, in accordance with the relevant test method.

Prepare and check the surfaces of the test material and end-tab material in the area to be bonded according to Section 6.

In conjunction with the adhesive manufacturers instructions and Section 7 apply and cure the adhesive, then assess the quality of the tabbed plate.

Assess the quality of the machined coupon according to Annex 7.

6.4. Coupon preparation - Procedure C

For untabbed and loose tabbed coupons (nb. tabs may be reusable)

Before machining into individual coupons, select the appropriate machining conditions according to Annex 2 and any material specification instructions for the material in use. Using the detailed instructions in Sections 3 and 4 then machine the individual coupon blanks and details (e.g. holes, notches), respectively.

Assess the quality of the machined coupon according to Annex 3 Section 7.

7. Inspection procedures

7.1. General aspects

The machined surfaces and edges of the finished coupons shall be free of visible flaws, scratches or imperfections when viewed with a low-power magnifying glass (approximately x 5 magnification). Rectangular bars, shall be free of twist and shall have perpendicular pairs of parallel surfaces. The surfaces and edges shall be free from scratches, etc. Each coupon shall be checked for conformity with these requirements by visual observation against straight edge, squares and plates, and by measuring with micrometer or callipers.

7.2. Detailed aspects

More detailed information regarding the quality of the test coupons is given in Section 8.

7.3. Coupon acceptance

Any coupon showing a measurable or observable departure from the requirements given above, or in the annexes, shall be rejected or machined to the correct size and shape before testing.

8. Test report

The test report shall include the following information:

a) A reference to this Draft, including whether Procedure A, B or C were used.

b) A description of the sample from which the test coupons were machined; including any relevant plate preparation standard, and applied conditions (e.g. cure temperature and time).

c) A precise description of the position and orientation of the test coupons, on a cutting plan.

d) The dimensions of the test coupons and the relevant test method standard(s).

e) The machining method and conditions used.

f) The bonding technique, surface preparation method and tab material used, if appropriate.

g) Any other relevant details or deviations from this Draft.

Bibliography

Relevant ISO test method standards are:

EN ISO 527 Part 4, Determination of tensile properties - Test conditions for isotropic and orthotropic fibre-reinforced plastic composites.

EN ISO 527 Part 5, Plastics - Determination of tensile properties - Test conditions for unidirectional fibre-reinforced plastic composites".

EN ISO 14129, Fibre-reinforced plastic composites - Determination of the in-plane shear stress/shear strain, including the in-plane shear modulus and strength, by the ±45° tension test method.

EN ISO 14125, Fibre-reinforced plastic composites of the flexural properties.

EN ISO 14130, Fibre-reinforced plastic composites - Determination of apparent interlaminar shear strength by short-beam method.

ISO 15024, Standard test method for mode I interlaminar fracture toughness, $G_{Ic,}$ of unidirectional fibre reinforced polymer matrix composites.

ISO 15310, Reinforced plastic - Determination of in-plane shear modulus by the plate twist method.

ASTM F22-65, Standard Test Method for Hydrophobic Surface Films by the Water-Break Test.

Contact details

Drills and routers

Composite Cutting Tools
Unit 4-5 Spectrum Way
20/20 Maidstone Industrial Estate
Maidstone
ME16 OLQ
01622 662323

RS Components Ltd
PO Box 99
Corby
Northamptonshire
NN17 9RS

Cutting wheels

D R Bennett
105A Barkby Rd
Leicester
LE4 7LG
0116 276 6715

Cranden Diamond Products
Mounts Hill
Benenden
Cranbrook
TN17 4ET
01580 241252

Laser cutting

Cirrus Laser Ltd
65 Victoria Rd
Burgess Hill
W. Sussex
RH15 9LN

Quantum Laser
Torrington Avenue
Tile Hill
Coventry
CV4 9HE

Abrasive water jet

Quantum Laser (Water jet division)
Torrington Avenue
Tile Hill
Coventry
CV4 9HE

Electrical discharge machining

Di-Spark Ltd
Unit 3b Wessex Gate
Horndean
Hampshire
PO8 9LP

Sparcatron Ltd
Eastington Trading Estate
Stonehouse
Glos.
GL10 3RZ

Coolant systems

Freddy Products (Environmental division)
Racecourse Rd
Pershore
Worcestershire
WR10 2EY
01386 561113