

Optimization of the wet lay-up/vacuum bag process for the fabrication of carbon fibre epoxy composites with high fibre fraction and low void content

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It is widely considered that wet layed-up carbon fibre epoxy composites fabricated by vacuum bagging suffer from an inherently high void content compared to autoclaved prepreg systems, and indeed can reach 10% or above in some cases. One reason for this is that the vacuum bag consolidation commonly employed is largely carried out without regard to the viscosity of the resin systems being used. In this investigation the wet lay-up technique is optimized by incorporating a dwell period at the start of the cure cycle to increase the resin viscosity before applying the bagging pressure. Resin viscosity is the critical parameter in producing fibre composites with low void content and a dwell time 'window' exists for each resin system within which high quality laminates can be consistently produced with up to 58% fibre volume fraction and less than 2% voidage. The 'window' exists between the same viscosity limits regardless of the resin system and temperature being used and therefore can be constructed for any resin system from a knowledge of its viscosity/temperature/time characteristics. The epoxy resins investigated were Ciba Geigy MY750/HY917/DY070 and LY1927/HY1927 with XA-S high strength carbon fibre both in uni- and bidirectional (0/90°) form.

Key words: composite materials; fabrication; wet lay-up; vacuum bagging; carbon fibres; epoxy resins

Developments in the fabrication of high quality carbon fibre reinforced plastics have traditionally come from the aerospace industry where prepreg materials and autoclaves are normally used. It is well known that to obtain optimum mechanical properties it is required to produce composite laminates with low voidage as well as fibre volume fractions of around 60%. Voids reduce the resin dominated properties such as compression strength,^{1, 2} and interlaminar shear strength (ILSS).³ Work by the author² has indicated that to obtain reasonable and consistent compression strengths it is desirable to maintain the level of randomly distributed voids below 2.5%. This void content also has the effect of reducing the ILSS by about 40–45%.³

The technique of producing composites of satisfactory quality in an autoclave has been described as more of an art than a science, as the appropriate processing

parameters need to be empirically determined. However, an improved understanding of these empirically derived cure cycles has recently been developed.^{4, 5} The cure cycle adopted for a particular resin, the lay-up and its associated tooling is designed to minimize these voids, and vacuum stripping, dwell time, pressurization time, dual vacuum, and dual pressure are all terms familiar to the autoclave operator.

There appear to be three sources of voids which can arise in epoxy prepreg laminates; two of these, retained solvent and entrapped air, are inherent in the lay-up and can be adequately removed by vacuum stripping early in the cure cycle. The third source is not as obvious and can in fact be created during the curing cycle by excess bleeding of the resin. This accounts for the tolerance and popularity of certain resin systems

which have been formulated with an intrinsic high viscosity ('zero bleed'); resin flow is sufficiently low in these systems to avoid resin starvation.

With a low viscosity resin system, however, careful control of the gelling process is required. Because convective heat transfer in an autoclave is dependent upon the pressure, the gelling time is determined by the moment at which the pressure is applied, and therefore pressurization time becomes the controlling factor in determining the quality of a laminate. The optimum time interval for which pressure can be applied is quite small (eg 10 min). If it is delayed, then excess resin flow causes voids; too early and the heat-up rate is increased, causing the viscosity to fall and too much resin is lost before gelation.

The heat-up cycle may also incorporate a dwell time at a temperature considerably below the final cure temperature. Where large thermal masses are involved this may be simply to allow the laminate to reach uniform temperature before pressurization. For low viscosity resins, however, it has been shown that a dwell time considerably improves the laminate quality by increasing the minimum viscosity before applying full pressure.

For non-aerospace composite structures cost is usually a major factor and can preclude the use of prepreg materials and autoclaves, yet high quality may still be required. The application of advanced composites in military bridging falls into this category (although the cost reduction in recent industrial grade prepgs means that these can now be considered). The purpose of the work reported here was, by learning from the principles derived for autoclave/prepg techniques, to investigate how far the optimization of the processing parameters could go towards improving the quality of wet layed-up carbon fibre laminates.

Consolidation of wet layed-up carbon fibre composites may be restricted to vacuum bag pressure alone, and this is commonly carried out without regard to the inherent viscosity of the resin system. When fabricating prepreg composites without an autoclave using vacuum bag pressure only, extended dwell periods may be carried out to fully outgas the resin.^{6,7} The experience of the author with hand layed-up wet resin techniques has been that simply extending the outgassing period of the resin is not sufficient to produce low voidage laminates. Those principles of prepreg/autoclave technology that seemed most worthy of investigation were control of the amount of resin applied to the fibres during wet lay-up, and the incorporation of a dwell period to increase the resin viscosity before applying the consolidation pressure. Control of the resin bleed-out by modification to the vacuum bagging pack was also considered.

EXPERIMENTAL DETAILS

Materials

The majority of the composite laminates were layed-up from Carrs unidirectional XA-S woven tape (340 g m⁻²), 100 mm in width, the dry woven tows being held together by a lightweight glass fibre weft. These

laminates were made 300 mm in length and each contained 7 plies of the woven tape layered unidirectionally to produce panels 2–3 mm in thickness. The investigation was later extended to include bidirectional XA-S 5-end satin weave (Fothergill A0046, 472 g m⁻²), 5 layers of this material being required to obtain 2–3 mm panel thickness.

Two epoxy laminating resin systems were investigated. One was MY750/HY917/DY070 (Ciba-Geigy) mixed in the ratio 100:87:1 by weight; it has a recommended gelling temperature of 80–100°C and can be fully cured by heating to 150°C for 3.5 h. The other resin system was Ciba LY1927/HY1927 (previous manufacturer's designation XD 927) mixed in the ratio 100:38; this is a cold-setting system with a recommended cure schedule of 16 h at RT plus 16 h at 100°C.

Resin viscosity measurements

The viscosities of freshly mixed resin samples were measured against time using a Ferranti co-axial cylinder viscometer. For the MY750 system this was carried out at a constant elevated temperature by placing the pot of resin in a water bath. It was considered that the recommended temperature of 80°C would cause the resin to gel too rapidly to allow a suitable dwell time to be incorporated into the laminate cure cycle, and therefore 70°C was chosen for the initial investigation. Viscosity measurements were also later carried out at 60°C for this resin. The viscosity/time curve for the cold curing LY1927 system was measured at room temperature.

Hand lay-up/vacuum bagging

The hand lay-up wet resin fabrication technique consisted of brushing the epoxy resin onto the dry carbon fibre cloth by hand, then using a paddle roller to ensure that all the tows in each fibre ply were well wetted out before proceeding to the next ply.

Initially varying amounts of total resin in the range 28–51 wt % were investigated, this eventually being standardized at an equal pot weight of resin to dry fibre material, resulting in an initial resin content in the lay-ups of 45–47 wt %. The resin was distributed as evenly as possible between all the plies.

The consolidation of the lay-ups was carried out on a purpose built vacuum bagging table (Fig. 1). A conventional bleed-out arrangement was used with

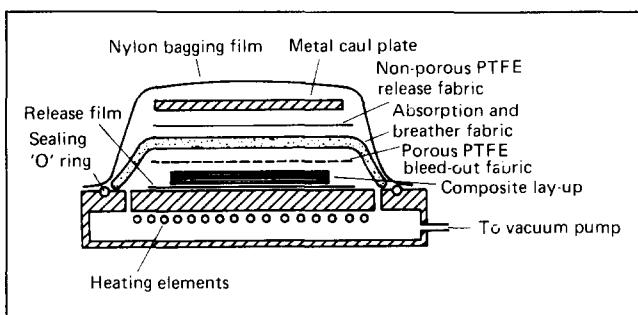


Fig. 1 Vacuum table and vacuum bagging arrangement

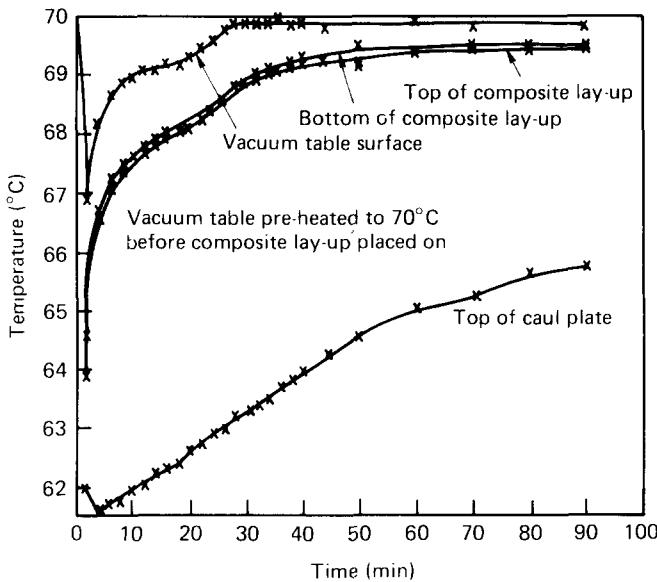


Fig. 2 Heat-up profile of vacuum table and composite lay-up at 70°C

bleed-out occurring from one side only through a porous bleed-out fabric to an absorption fabric which also acted as a breather. A caul plate above ensured panel flatness. In a few experiments a modification was made to the bleed-out/absorption fabrics to investigate whether the amount of resin bleed-out could be controlled by this approach.

For the hot-setting resin the lay-up was heated directly through the base plate by the built-in electric elements which were controlled from an adjacent Cambridge temperature controller. Thermocouples were placed above and below the lay-up to monitor the resin temperature and the table was evacuated using an Edwards 18 two-stage rotary pump. The table was pre-heated before placing the MY750 resin lay-ups onto it, gelling temperatures of 70°C and then 60°C being investigated. The vacuum bag could be sealed by clamping between a metal frame and a rubber 'O' ring. An insulated blanket was then placed over the top of the table to maintain a constant temperature.

The lay-ups reached the set gelling temperature very quickly at 60°C (*e.g.* ~2 min) but at 70°C there was a 30 min heat up time for the lay-up (see Fig. 2). For the initial 'control' laminates, the vacuum pump was switched on immediately; subsequent lay-ups were given a dwell period before consolidation, *i.e.* the curing reaction was allowed to proceed until the resin viscosity increased significantly. The times of the dwell periods were chosen in an iterative manner, evaluating each laminate for voids and fibre fraction before modifying the dwell time for the next laminate. For precise control the dwell times were set on a digital timer switch connected to the vacuum pump. The weights of the fibre cloth, resin used, and cured laminate were each recorded. The laminates were then fully post-cured at the manufacturer's recommended temperatures.

Laminate density measurements

Each laminate was trimmed around the edges to remove the slight taper, then the density of the panel

was determined by the Archimedes method. As a check the densities of two small samples, one from each end, were also determined using a series of zinc chloride density tubes graduated in steps of 0.01 g cm⁻³.

Fibre volume fraction and void contents

Each laminate was ultrasonically C-scanned in through-transmission using a Sonic MK4 flaw detector and a Versiscan scanning system with 10 MHz collimated probes. The signal was quantized into six steps of 2 dB gain intervals, each step being digitized into a different colour on a computer monitor and subsequently an ink jet colour printer for hard copies.

The equipment has previously been calibrated to correlate ultrasonic attenuation coefficients with laminate void contents, the latter being measured with an AMS 40-10 image analyser.

Attenuation readings were taken for each of the laminates and converted to a void content for each colour in the C-scan. The void content levels were then factored by the estimated area percentage of that colour in the scan to provide a total void content for the whole panel. The fibre volume fraction for each laminate was then obtained from the rule-of-mixtures equation shown in the Appendix

$$V_f = \frac{\rho_c - \rho_r (1 - V_v)}{(\rho_f - \rho_r)} \quad (1)$$

where ρ_c , ρ_f and ρ_r are the densities of composite, fibre and resin (the latter values from manufacturer's data) and V_v is the volume fraction of voids obtained from the C-scans.

THEORETICAL DERIVATION

The theoretical percentage resin bleed-out for any given fibre volume fraction (V_f) can be calculated from the weight of fibres used to produce the laminate, the initial weight of resin used and the final laminate weight. The weight fraction of resin in laminate

$$= \frac{r_2}{r_2 + m_f} = 1 - W_f \quad (2)$$

where m_f = weight of fibres,
 r_1 = weight of resin before bleed-out,
 r_2 = weight of resin in laminate after bleed-out and
 W_f = weight fraction of fibres in laminate.

The weight of resin bleed-out = $r_1 - r_2$, and the percentage weight of resin bleed-out

$$\frac{r_1 - r_2}{m_f + r_1} \times 100 = \left[\frac{r_1}{m_f + r_1} - \frac{m_f (1 - W_f)}{W_f (m_f + r_1)} \right] \times 100 \quad (3)$$

If W_{r1} = the weight fraction of resin before bleed-out

$$W_{r1} = \frac{r_1}{r_1 + m_f} \quad \text{and} \quad \frac{m_f}{m_f + r_1} = 1 - W_{r1}$$

Therefore from Equation (3), the percentage weight of resin bleed-out

$$= \left\{ W_{r1} - \left[\frac{(1 - W_{r1})(1 - W_f)}{W_f} \right] \right\} \times 100$$

or, expressed in terms of the percentage of resin before bleed-out, $\%r_1$, the percentage weight of resin bleed-out

$$= \%r_1 - \left[\frac{(100 - \%r_1)(1 - W_f)}{W_f} \right] \quad (4)$$

The weight fraction of fibres is related to the volume fraction (V_f), by

$$V_f = \frac{W_f}{W_f + \left(\frac{\rho_f}{\rho_r} \right) W_r} \quad (5)$$

where ρ_f and ρ_r are the densities of the fibre and resin respectively, and W_r is the weight fraction of resin in the laminate.

Combining Equations (4) and (5) expresses the fibre volume fraction, V_f , of the laminate in terms of the initial resin content in the lay-up and the weight percentage bleed-out necessary to produce that V_f . Fig. 3 shows the relationship between these weight percentage bleed-out values and V_f for initial resin

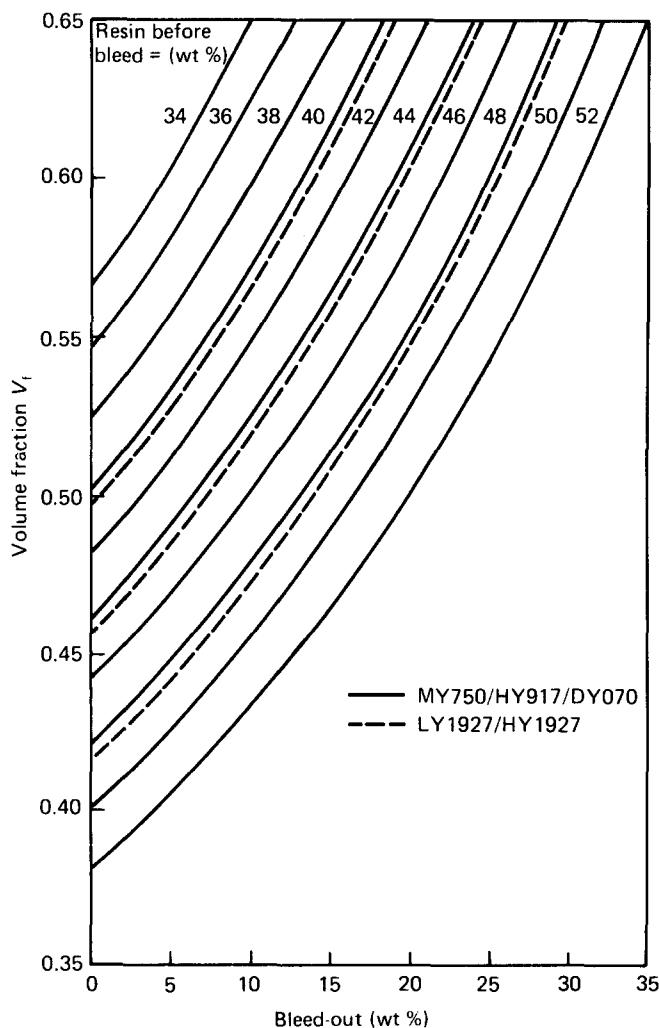


Fig. 3 Theoretical amounts of resin bleed-out for various V_f values and initial resin contents. Numbers on curve represent the wt% resin before bleed

contents varying from 34 to 52 wt %. This covers the range likely to be produced in practice by hand lay-up using wet resin; the curves are slightly displaced for the MY750 and LY1927 resin systems because of the different densities of these resins. The curves are theoretical in that they do not take into account void formation in the laminate, but they do give an indication of the amount of resin bleed-out that should be obtained for an optimum V_f value of 0.6.

EXPERIMENTAL RESULTS

The viscosities of the two resin systems have been plotted with time in Fig. 4. The behaviour of the MY750/HY917/1% DY070 system is shown at temperatures of both 70°C and 60°C up to 800 poise (80 Pas); viscosity/time readings for the LY1927 system were only obtained up to about 250 poise (25 Pas) as the preceding dwell time experiments with MY750 resin has shown that this provided adequate data.

Table 1 lists the results obtained from the dwell time experiments using the MY750 resin with unidirectional (U/D) carbon fibre material for gelling temperatures of 80°C, 70°C and 60°C. The table shows the initial resin content, amount of bleed-out and resin remaining in each laminate panel. From the latter value the theoretical V_f (ie assuming no voids) could be calculated from Equation (5), knowing the fibre and resin densities. In practice this was made easier by making use of the chart in Fig. 14 (a similar chart was plotted for the LY1927 resin). The laminate densities are also shown in Table 1 together with the void contents obtained from C-scanning; these were combined using Equation (1) to give the actual fibre volume fraction (V_f) of each laminate.

Panel numbers 01–03 were used to establish the effect of varying the initial resin content on the laminate voidage and fibre volume fraction. They were fabricated with no dwell period, the vacuum being applied immediately, and were gelled at 80°C. From

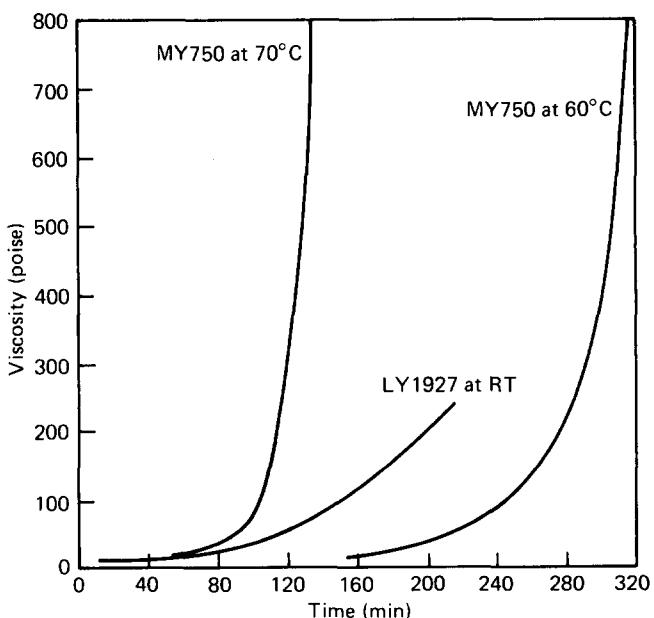


Fig. 4 Viscosity against time for MY750 and LY1927 resins

these laminates it was apparent that the gel temperature of 80°C was too high to allow adequate control of the cure process and the temperature was subsequently reduced to 70°C and 60°C for the actual dwell time experiments.

Panel numbers 04–10 were gelled at 70°C for dwell periods varying from zero to 2 h 45 min respectively, whilst panel numbers 11–20 were gelled at 60°C for dwell periods from zero to 5 h. Panel numbers 11–13, as well as acting as 'control' experiments with zero dwell time, were also used to observe the effect of varying the bleeder and absorption fabrics respectively.

Table 2 compares the fabrication of bidirectional laminates with zero dwell and the optimum dwell time selected from the data in Table 1. Initially very high void contents were obtained in the control laminates when using this woven fabric (panel numbers 21 and 22) as confirmed by the low density results, and it was necessary to modify the wetting-out procedure by warming the pot of resin slightly to around 40°C before lay-up and rolling out each ply extensively with the paddle roller. A higher initial resin content of 56 wt % (panel number 24) did not result in any further improvement.

The results of the dwell time experiments for the cold curing LY1927 resin are presented in Table 3. These were all carried out at ambient room temperature which varied only between 18 and 21°C. The dwell period was varied between zero and 3 h 40 min (panel numbers 27–33), these times being selected from the optimum results for the MY750 laminates and adjusted to obtain similar viscosities for the LY1927 system. The quality achieved in the optimized MY750 laminates could not be reproduced exactly for those fabricated from LY1927, and panel numbers 34–36 were additional zero dwell time experiments carried out to determine the reason for this.

The C-scans of the laminates were produced in a digitized colour format, most of which would not be very meaningful in black and white print. However, Fig. 5 does allow comparison between control laminates (zero dwell) of MY750 and LY1927 and the optimized MY750 with a dwell of 2 h 13 min at 70°C. The white areas are high voidage regions up to approximately 6% voids whereas the lighter grey areas in Fig. 5c contain only around 1% voids.

DISCUSSION

One of the possible disadvantages of hand lay-up using wet resins is the lack of control of the initial resin content applied to the fibres, but an investigation of a range of resin contents (panel numbers 01–03) in which it was varied from 28–51 wt % showed that, although the resulting resin bleed-out was very different in each case, the resin remaining in the cured laminates was the same. The quality of these laminates was also very similar in terms of fibre fraction and void content as determined from the C-scan results. The initial resin content was therefore not critical in determining the quality of the laminate produced, and for the main investigation a 1:1 ratio of fibre to resin pot weight was adopted for convenience. This resulted in initial resin

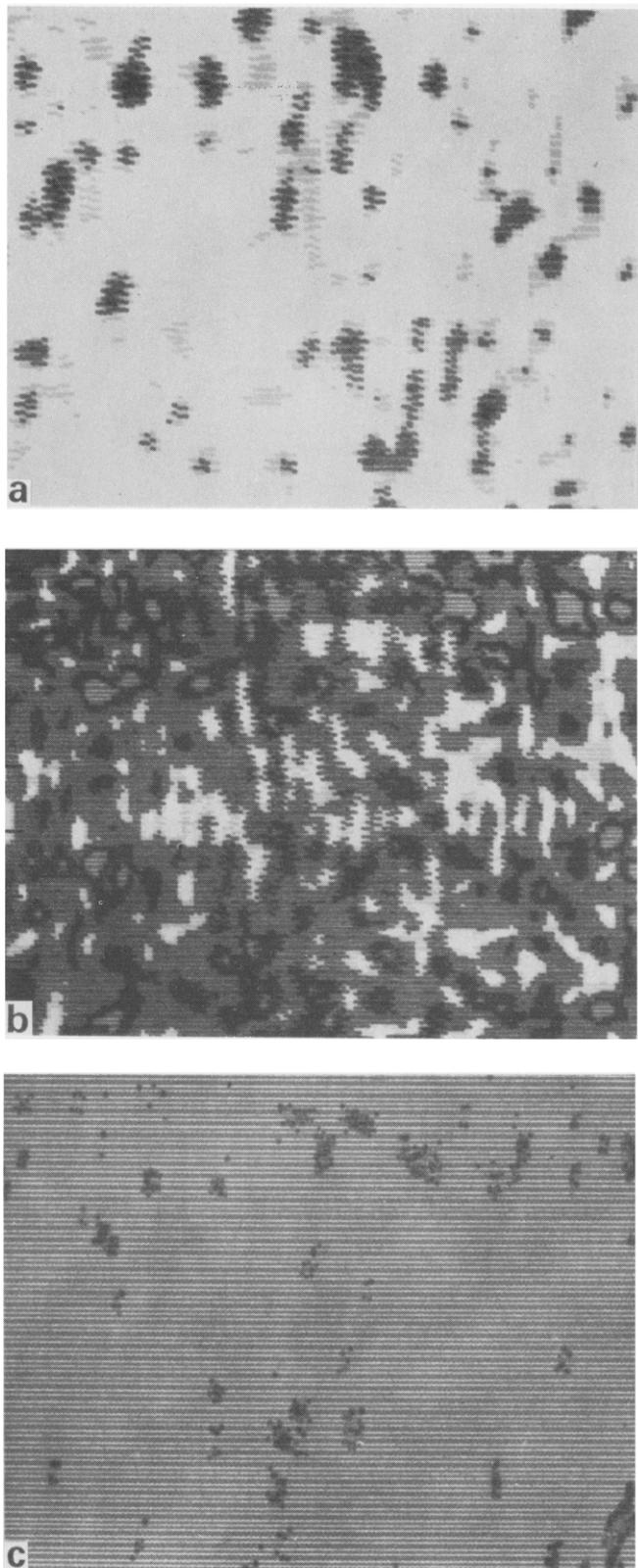


Fig. 5 Ultrasonic C-scans showing (a) LY1927 zero dwell, 5.3% voids, (b) MY750 zero dwell, 3.8% voids and (c) MY750 optimum dwell at 70°C, 1.3% voids (white = high voidage, dark grey = medium voidage and medium grey = low voidage)

contents in the lay-up generally in the range 44–47 wt %.

The theoretical fibre volume fractions (V_f) listed in Table 1 are derived from Fig. 3 and assume zero void

content, whereas the V_f obtained from a C-scan utilizes Equation (1), which takes into account the voidage, and is based on the assumption that the voids are present in the composite in lieu of matrix resin rather than in addition to the matrix. Therefore the summation of V_f and void figures from C-scanning should equal the theoretical V_f derived from Fig. 3. In most cases, see Table 1, the agreement is good, considering the problems involved in any experimental measurement of void content.

Another parameter which was considered to be a possible factor in controlling resin bleed-out and therefore the quality of the laminate was the bleeder/absorption arrangement adopted in the vacuum bagging procedure. This was investigated in two ways: first, the standard weight of absorption fabric (339 g m^{-2}) was replaced by a lighter (150 g m^{-2}) fabric of which 1 and 2 layers were compared (panel numbers 11 and 12). The second variation was to change the porous PTFE-coated glass bleed-out fabric for a perforated Teflon film containing holes of approximately 1 mm diameter. None of these modifications changed the bleed-out characteristics, the laminate resin weight being identical in all three cases, and the densities of the panels were also very similar. The different bleed-out weights given in Table 1 for these panels were as a result of different initial resin contents. It does not seem probable therefore that control of the amount of resin bleed-out can be achieved simply by varying the arrangement of the vacuum bleed-out/absorption pack.

In Fig. 6 the viscosity/time curves for the MY750 resin have been combined with the quality assessment (V_f and void content) of the laminates to produce an optimum viscosity range for the application of the vacuum consolidation pressure. High voidage occurred in the laminates when the resin viscosity was low ($<75 \text{ poise}$), and although the voidage level was found to be low when the resin viscosity was high ($>165 \text{ poise}$) the V_f was correspondingly low due to resin richness and never exceeded 49%. At a gel temperature of 70°C the 30 min heat-up time for the lay-up (see Fig. 2), if subtracted from the dwell times listed in Table 1, results in the same viscosity limits for both temperatures, 60°C and 70°C (the heat-up time at 60°C was only 2 min and was neglected). Constructing these viscosity limits on the viscosity/time curves produces the dwell time 'windows' shown in Fig. 6. For optimum laminate quality the vacuum consolidation pressure should be applied within these windows at each gel temperature. Laminates can then be produced with a void content less than 2% and a fibre volume fraction up to 58%. The window at 70°C is only about 10 min wide, which in practice may present difficulty when variations in heat-up rate are taken into account. However, due to the slower rise in viscosity of the MY750 resin at 60°C the window is extended to 36 min at this gelling temperature.

Optical micrographs of the improvement obtained by incorporating a dwell period into the cure cycle can be seen in Fig. 7 which compares a zero dwell (control) panel and those fabricated at the optimum dwell times for 60°C and 70°C gelling temperatures. Fig. 7(a)

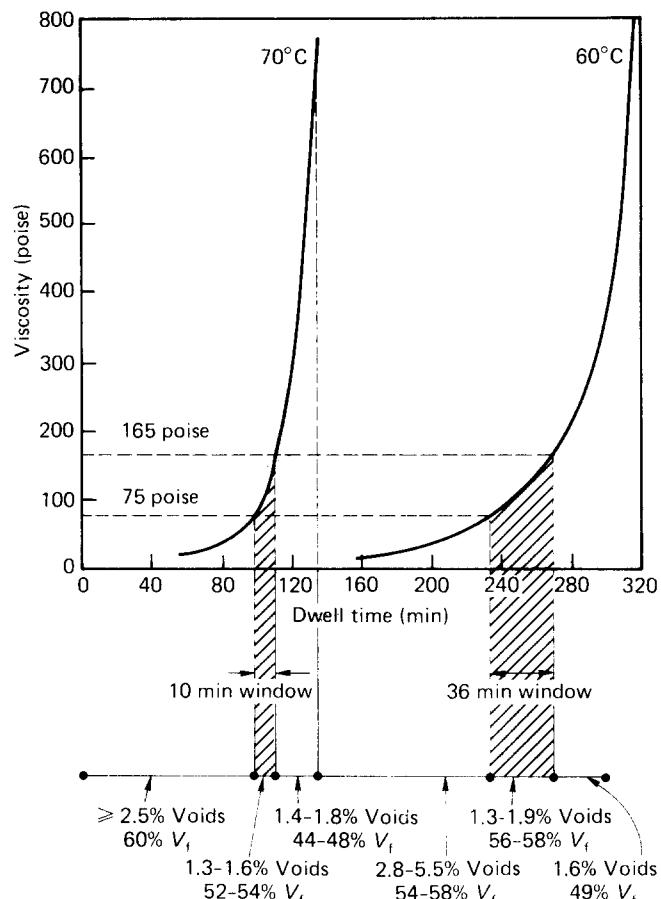


Fig. 6 Dwell time windows for MY750 composites at 70°C and 60°C

reveals that two types of voids are present in the non-optimized laminate; small spherical voids are seen in the middle of the fibre tows whereas large elongated voids are present in the resin rich areas between the tow boundaries. It is apparent from the actual amount of resin bleed-out obtained (see Table 1) when comparing this to the percentage that should have occurred, see Fig. 3, that the elongated inter-ply type voids are caused by overbleeding of the matrix due to the resin viscosity being too low at the time of consolidation. This overbleeding of resin is probably facilitated by the easy flow paths between the tows in the woven fibre material being used.

Voids of this type are virtually eliminated in laminates where the resin viscosity is allowed to rise before the vacuum pump is switched on, as illustrated in Figs 7(b) and (c) (the darker tow boundary at the bottom of Fig. 7(b) contains the glass weft which holds the tows together). This principle of a dwell period in the cure cycle is therefore similar to that which is sometimes applied to a low viscosity non-zero bleed prepreg system.^{5,6} Wet lay-up usually differs from a prepreg system in that higher initial resin contents are used, but this still results in overbleeding if optimized process conditions are not used.

The smaller type of voids which are evident within the tows may also have formed due to overbleeding, or may have occurred by air entrapment during lay-up and

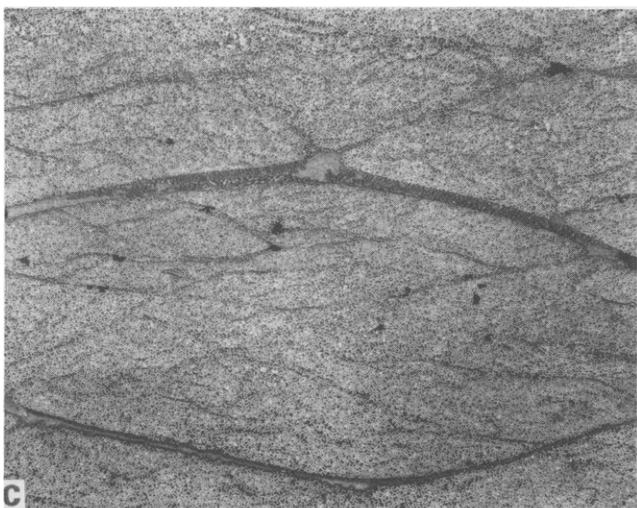
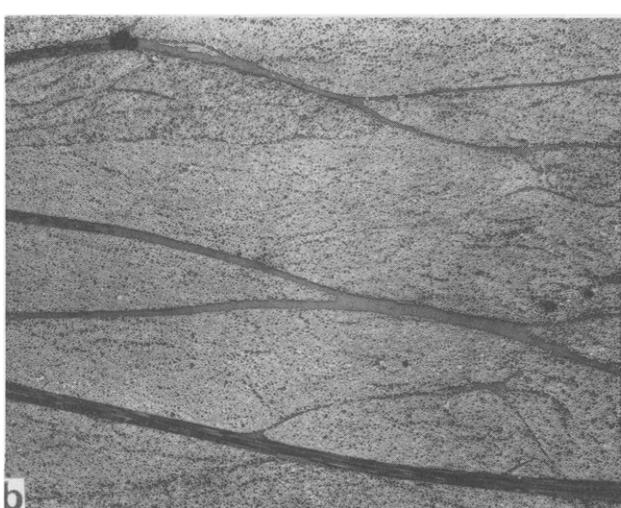
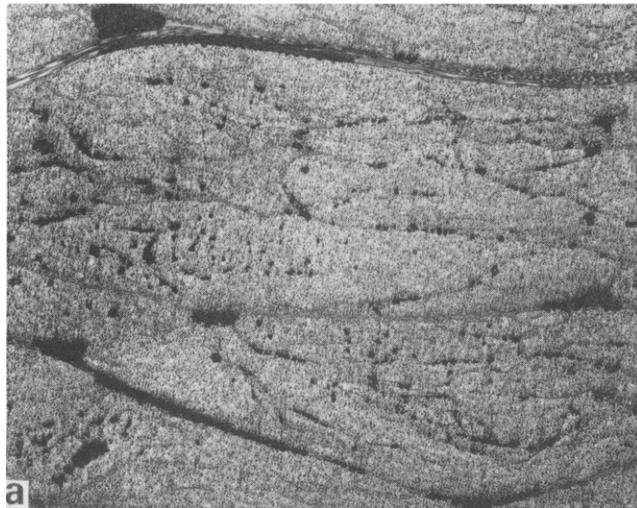


Fig. 7 U/D laminate with MY750 resin at (a) zero dwell (control), (b) optimum dwell (2 h 13 min) at 70°C and (c) optimum dwell (4 h 15 min) at 60°C. Magnification $\times 50$

not been removed during consolidation. If the latter, then the higher viscosity of the resin after the dwell period may aid their collapse as mentioned by Hayes⁶ for high viscosity prepreg systems. There are very few of these voids in the optimized laminates of Figs 7(b)

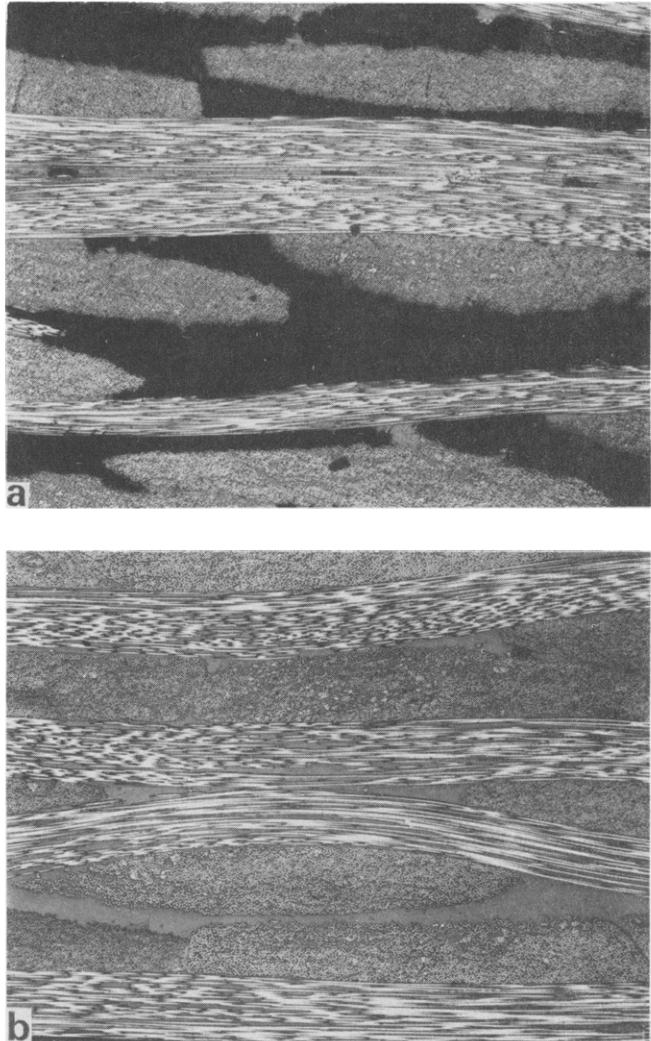


Fig. 8 Bidirectional (0/90°) laminate with MY750 resin at (a) zero dwell (control) and (b) optimum dwell (4 h 15 min) at 60°C. Magnification $\times 50$

and (c). It would appear however that a low void composite is not possible at a volume fraction of 60%, and a compromise must be made with a lower V_f of around 56% to achieve the minimum void content of just over 1%.

Bidirectional (0/90°) laminates were also fabricated using the optimized dwell time selected from Fig. 6 of 4 h 15 min at 60°C. These were compared with non-optimized zero dwell time laminates and the data listed in Table 2. Even lower composite densities were measured for the non-optimized bidirectional panels than the U/D control laminates, and Fig. 8(a) reveals gross voidage between the fibre tows where extensive overbleeding has occurred. This is considerably worse than the U/D laminates, most probably due to the additional space between the woven tows, as a result of extra crimp which has presented even easier flow paths for the matrix. The optimized dwell conditions, however, as shown in Fig. 8(b) have eliminated this problem entirely, with (again) a very low void content of 1%, but the decreased packing density of this woven fabric reduced the V_f to 52%. It would appear though that the desirable viscosity range and therefore the

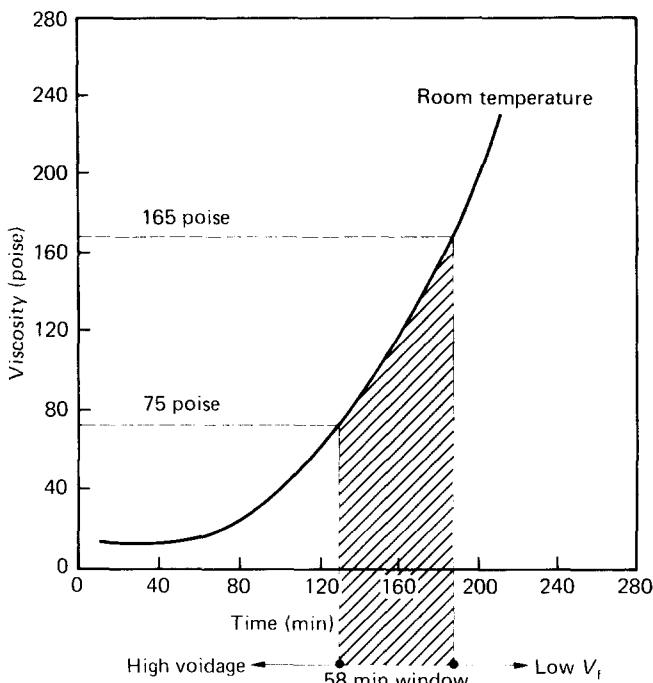


Fig. 9 Predicted dwell time window for LY1927 composites at RT (18–20°C)

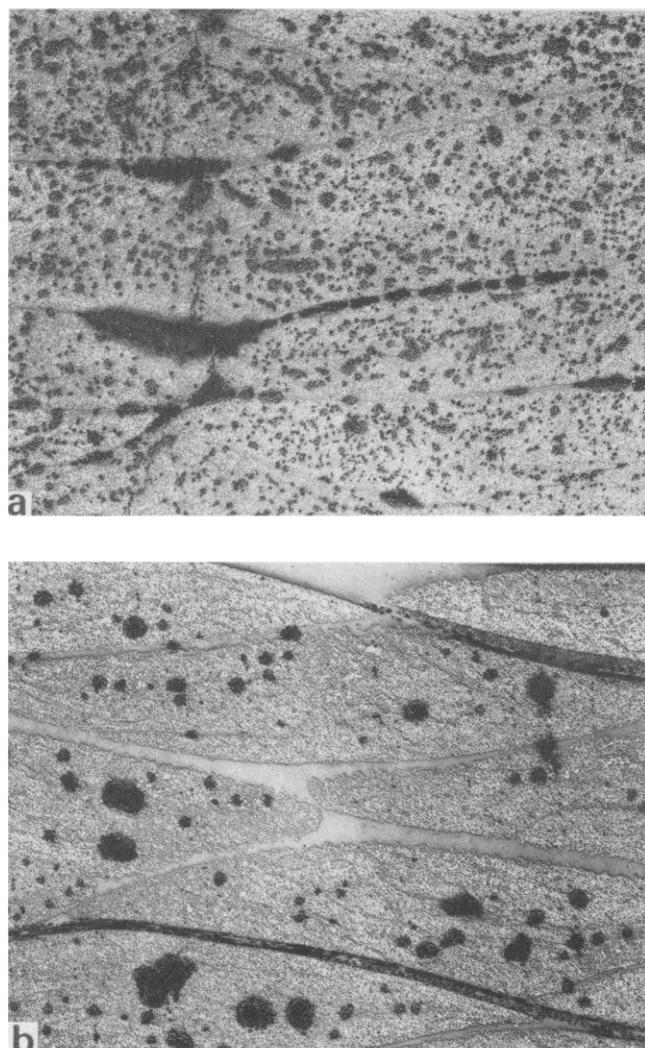


Fig. 10 U/D laminate with LY1927 resin at (a) zero dwell (control) and (b) optimum dwell at RT. Magnification $\times 50$

optimized dwell periods for a specific gelling temperature are independent of the type of dry carbon fibre fabric being used.

The viscosity/time curve of the LY1927/HY1927 resin system is replotted from Fig. 4 and shown in Fig. 9 with the optimum viscosity range limits established for the MY750 resin system constructed on it. This has resulted in a predicted dwell time window approximately 58 min wide which formed the basis of the experiments reported in Table 3. Fig. 10(a) shows an example of a zero dwell composite (panel number 29) of considerably high voidage; the bleed-out figures for laminates such as these resulted in very high theoretical fibre volume fractions. As well as gross voidage at the tow boundaries of the type due to overbleeding there was also a very large number of smaller voids within each tow.

With the laminates fabricated using the LY1927 resin there was not the same agreement between the theoretical V_f values derived from Fig. 3 and the summation of the fibre and void contents obtained from C-scanning, but the reason for this is not known. The significantly higher void content resulting from the use of this resin system compared to MY750 was confirmed in the other control panels, and was also observed repeatedly in other similar laminates not associated with this investigation, and resulted in large decreases in the compression strength of the material.² However, a dwell period within the predicted window (panel number 29 was dwelled for 2 h 30 min) again resulted in a significant reduction of voidage (see Fig 10(b)), the large interply voids having been eliminated which is consistent with the lower bleed-out figure for this panel. The many smaller voids within the tows were also much reduced in number, but not to the same extent as with the optimized MY750 laminates. Dwell times longer than the predicted window (panel numbers 32 and 33), although still having lower voidage, also had a low V_f of around 47%, which had been the case with the MY750 composites. A dwell period just inside the window of 2 h 55 min (panel number 31) was similar in quality to panels beyond the window (panel numbers 32 and 33) and therefore suggests the LY1927 dwell window is slightly narrower than predicted.

The higher voidage with LY1927 resin compared to MY750 seems not to be related to a difference in viscosity/time characteristics as the initial viscosity of LY1927 and its rate of increase with time, although shifted up the time axis, is very similar to that of MY750 at 60°C. Two other possible reasons for the large number of tiny voids present in those LY1927 laminates produced without a dwell period were thought to be air bubbles incorporated into the resin during mixing and low vapour point constituents being drawn off under vacuum during consolidation. Additional laminates (panel numbers 34–36) were fabricated in order to reduce or eliminate these possible effects. However, neither degassing the resin in the pot prior to laying-up (see Fig. 11(a)) nor reducing the vacuum level by almost half (Fig. 11(b)) reduced the voids significantly. Examination of these voids at the higher magnification of Fig. 12 reveals that they are

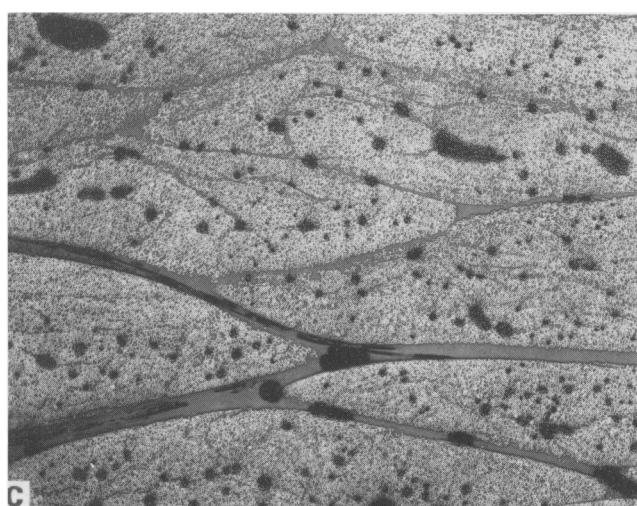
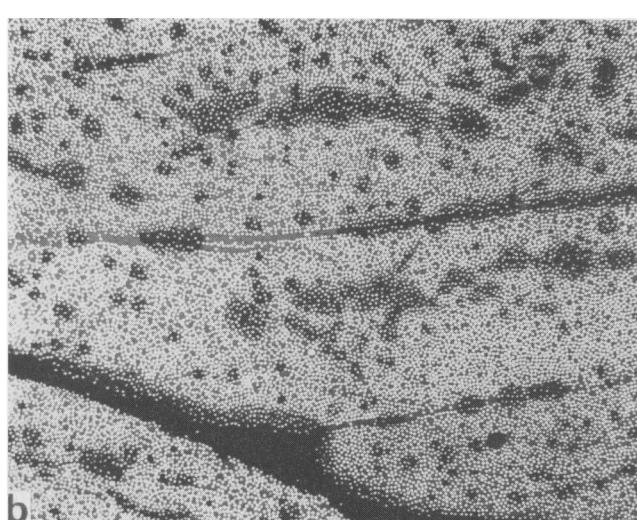
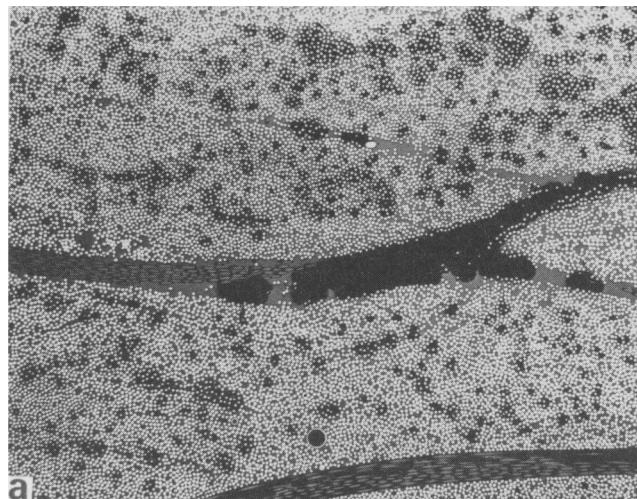


Fig. 11 LY1927 resin laminate with (a) resin degassed before laying-up, (b) vacuum consolidation reduced to 0.6 atm (8.8 psi) and (c) consolidated by dead weight only (4.2 psi). Magnification: (a) and (b) $\times 75$, (c) $\times 50$

different in nature to those of an MY750 laminate, Fig. 12(b) showing that in the LY1927 material fibres can be observed within the voids themselves. This was not the case with MY750 voids (see Fig. 12(a)). This effect

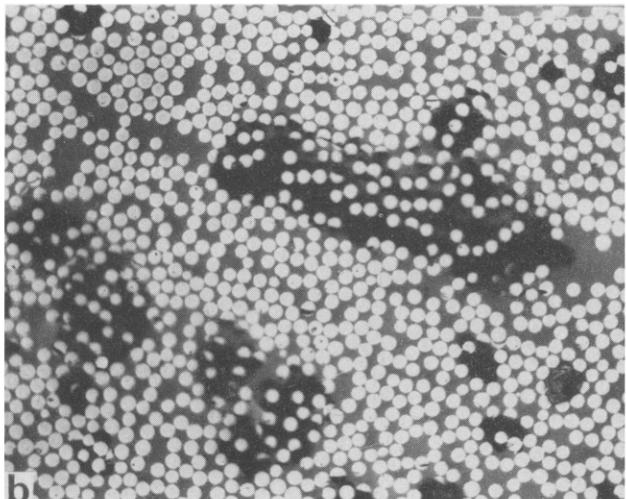
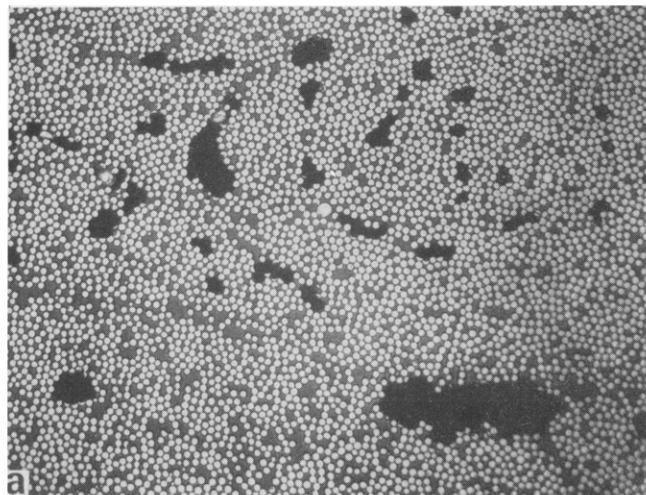


Fig. 12 Comparison of the nature of voids with (a) MY750 laminate and (b) LY1927 laminate. Magnification (a) $\times 100$, (b) $\times 200$

appeared to be consistent with poorer wetting out of the carbon fibre surface as the application of dead weight consolidation, which avoids the use of vacuum altogether, did not eliminate this type of void (Fig. 11(c)). To subject the resins to a different type of fibre surface a comparison was made of the wet-out of single plies of glass fibre tape for both MY750 and LY1927 resin systems (see Fig. 13), but the effect was again clearly evident, suggesting that LY1927 has inherently poorer wetting-out characteristics unrelated to the exact nature of the fibre surface. This appears to be the reason for the significantly higher voidage produced in composites with this resin.

CONCLUSIONS

- Providing that good wetting out of the fibre tows is assured during lay-up then the viscosity of the resin matrix at the beginning of vacuum bag consolidation is the critical parameter in the fabrication of high V_f , low voidage carbon fibre epoxy composites using wet resin techniques. Neither the initial resin content of the lay-up nor

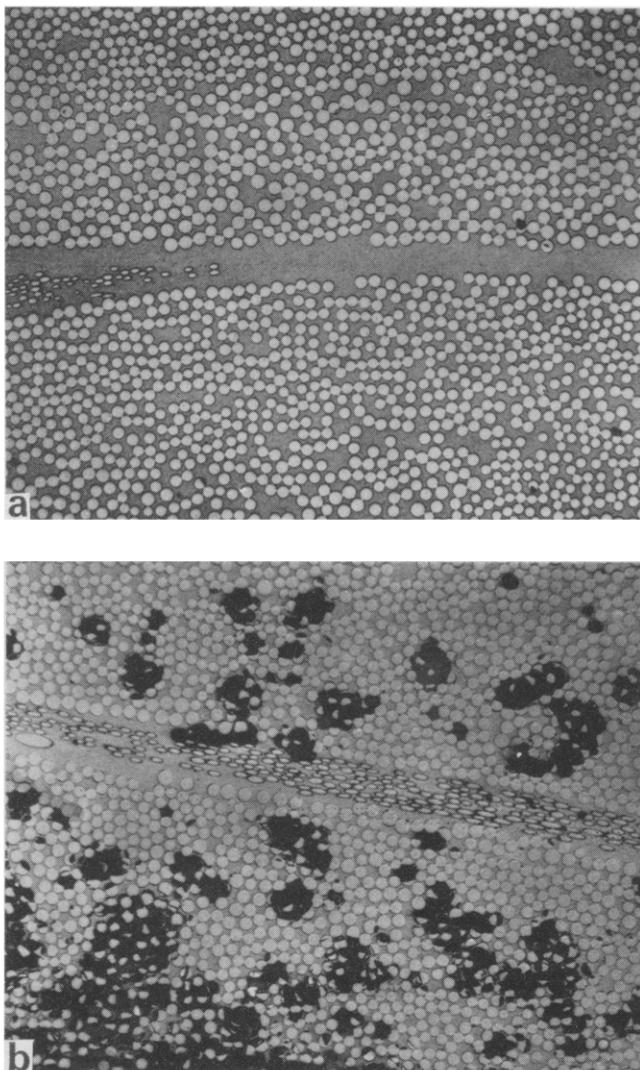


Fig. 13 Glass fibre single ply lay-ups with (a) MY750 resin and (b) LY1927 resin. Magnification $\times 200$

variations in the bleed-out/absorption arrangement have much effect.

- It is necessary to allow the resin viscosity to increase to a certain value by incorporating a dwell period into the cure cycle before applying the consolidation pressure.
- A dwell time 'window' exists for each resin system within which high quality laminates can be consistently produced with up to 58% V_f and less than 2% voidage. Beyond this window the viscosity is too high to allow sufficient resin to bleed out.
- The 'window' exists between the same viscosity limits regardless of the resin system and temperature being used and therefore can be determined for any resin system simply from a knowledge of its viscosity/temperature/time characteristics, allowing the optimum dwell period to be predicted.

APPENDIX

The rule of mixtures equation for composite density when no voids are present is given by

$$\rho_c = \rho_f V_f + \rho_r (1 - V_f)$$

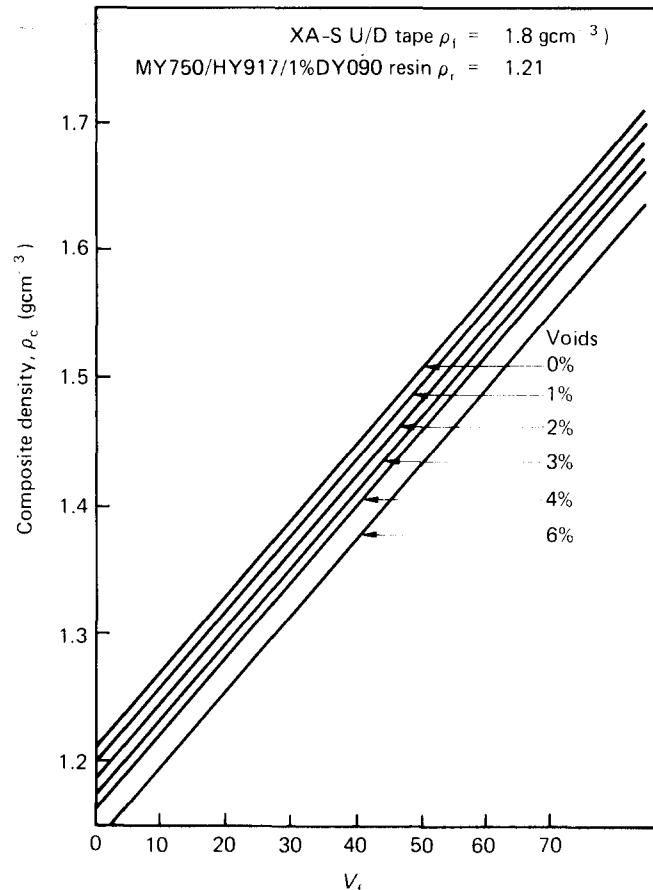


Fig. 14 Composite density rule of mixtures for various void contents

where ρ_c , ρ_f , ρ_r are the densities of the composite, fibre and resin, respectively, and V_f and V_r are the fibre and resin volume fractions, i.e

$$V_f + V_r = 1$$

When voids are present in the laminate in lieu of matrix resin then

$$V_f + V_r + V_v = 1$$

where V_v is the volume fraction of voids.

Therefore

$$\begin{aligned} \rho_c &= \rho_f V_f + \rho_r V_r + \rho_v V_v \\ &= \rho_f V_f + \rho_r (1 - V_f - V_v) + 0 \end{aligned}$$

The fibre volume fraction is given by

$$V_f = \frac{\rho_c - \rho_r (1 - V_v)}{(\rho_f - \rho_r)} \quad (1)$$

This equation has been plotted out in Fig. 14 for MY750 resin ($\rho_r = 1.21 \text{ g cm}^{-3}$) and XA-S carbon fibres ($\rho_f = 1.8 \text{ g cm}^{-3}$) for a series of void contents from 0 to 6%. The V_f for a laminate can then be easily found from a knowledge of its density and void content.

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