Advanced Thermoplastics and their Composites [and Discussion]

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Advanced thermoplastics and their composites

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Composite materials, be they highly oriented continous-fibre structural materials or short-fibre and even particulate composites, remain critically dependent upon matrix properties.

Interest in the use of thermoplastic matrices has spread from conventional injection moulding composites into collimated continuous fibre materials. As the critical applications of such materials have been explored, so the demands on matrix properties have become clearer, and potentially more stringent.

The demand for advanced properties is set primarily by response of the matrix, and fibre matrix interface to hostile working environments involving temperature, chemical attack, and physical abuse. Such properties are a reflection of molecular structures and their resulting morphology, but the achievement of desirable properties is bounded also by synthesis on the one hand and component fabrication on the other. By definition, such highly engineered materials and their related processes must exhibit 'reliability'.

The paper attempts to relate the interaction between structure and properties for such materials concentrating on high-performance structural composites and a view of the broad requirements if such materials are to have use.

1. THEME

To illustrate their potential for multidisciplinary scientific and technological drives, we have chosen to concentrate on continuous-aligned-fibre composites aimed at aerospace structural applications. Although families of composites designed for less demanding applications can be easily produced, concentration on this application illustrates the breadth of science and technology that will be used in the development of relatively new materials, offering potential advantages to designers in structural composites.

2. THE PROSPECT

The use of fibrous composites in aircraft structures began with the dawn of flying, where, no doubt, the choice of woods presented the constructor with similar issues of fibre alignment, environmental resistance and toughness. Such work produced the *Spruce Goose*, beloved of Howard Hughes, and the ubiquitous *Mosquito* of World War II. It was, however, the advent of carbon fibre that led to rapid growth in the structural design of aligned-fibre composite materials aimed at mass and performance gains in military and commercial aircraft. Numerous illustrations of the progress achieved include such crafts as the AV8B and the Boeing 757.

The progress is shown (table 1) by relative specific performance, although the issues are more complex. The prospect for the major markets in high-performance materials (figure 1) drives the world's materials companies to work closely with their customers, the international aerospace companies. In this context, 1985 may have been a watershed in the industry as a spate of acquisitions saw the major international chemical firms positioning themselves to take advantage of opportunities that will occur in the next decade and beyond.†

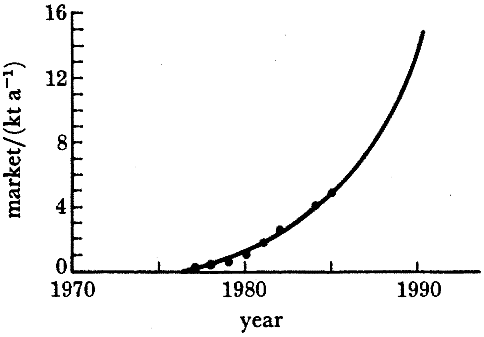

FIGURE 1. High-performance composites.

TABLE 1. RELATIVE PROPERTIES

	carbon-fibre composite	titanium	aluminum 2024
density/(kg m^{-3})	1605.457	4428.80	2768.03
tensile modulus/GPa	52.4–127.6	110.3	73.1
tensile strength/MPa	690–1896	952–1172	186–483
interlaminar shear strength/MPa	110.3	690–758	124–283
relative specific modulus	1.2–3.0	0.94	1.0
relative specific tensile strength	2.5–6.9	1.2–1.5	1.0

Much activity in high-performance composites has resulted from a base of thermosetting resins. The reasons for this are not difficult to understand. There was already a base of long-fibre composites with brittle thermosetting resin systems, the latter having modest use without fibre reinforcement, and the low viscosity of prepolymers presented an easy route to impregnation. Further, the cross-linked nature presented engineers with reasonable assurance of environmental resistance. Thermoplastics, by contrast, had traditionally been designated for product forms for high-productivity moulding and extrusion, including the benefits of *short*-fibre reinforcement.

However, the limitations of the then existing thermosetting systems, namely brittleness, sensitivity to water, and fabrication costs, had driven the industry to examination of thermoplastics as early as 1974, when secondary aircraft structure based on polysulphone amorphous thermoplastics was aimed at toughness and fabrication costs. Sadly, the environmental properties of the available thermoplastics, capable of operation at the desired temperatures were limited and this subject was relatively dormant until 1982 with the advent

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† Units in this paper have been converted to the SI system. 1 kg m^{-3} ≈ 3.61 × 10^{-5} lb in^{-3}; 1 Pa ≈ 1.45 × 10^{-4} lbf in^{-2}.

of the aromatic crystalline polymer polyetheretherketone, offering a balance of properties of renewed interest to the structural composite engineer.

The target involves composite toughness, reduction in fabrication costs, operation at higher temperatures and in adverse environments and drives for the further development of advanced thermoplastics matrices for continous-aligned-fibre structural composites.

3. Matrix requirements

The demands on the polymeric matrices of continuous fibre composites, generally representing some 40 vol. % or less of the composite, presents a spectrum of property demands that will lead to the generation of thermoplastic polymers tailored to these applications.

3.1. *Stiffness and yield strength*

Matrix stiffness is important, being that property which controls fibre buckling in all-important compressive loading. Whereas in tensile performance, composite properties are fibre dominated, under compressive loadings including those associated with flexure, freedom for the fibres to buckle results in premature failure and inadequate realization of fibre properties. This suggests that resin systems with stiffnesses significantly less than 3.5–4.0 GPa will have limited applicability in truly structural materials.

3.2. *Temperature performance*

The industry will demand a range of materials exhibiting temperature performance to suit the application, depending on the compromises involved. At least two major requirements are identified in the aerospace industry representing a continuous service temperature of 100 °C, primarily for commercial aerospace applications and operation at 180 °C, primarily for more advanced military requirements. This will not represent all the demands, but is sufficient to illustrate the requirements of such new materials.

A crucial issue surrounding the debate on temperature performance of thermoplastics, is the choice of amorphous or semicrystalline resins. As shown in figure 2, describing the change in stiffness of two commercially available high-temperature thermoplastic resins, the property retention up to the glass transition temperature, T_g, and the degree of property retention between T_g and T_m, the melting point, is a dominating feature. Today's view supports

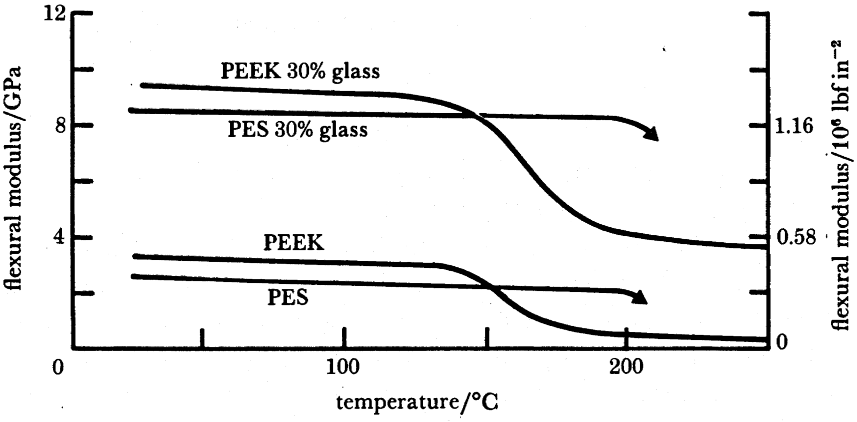

Figure 2. Flexural modules against temperature (PEEK and PES).

concentration on the semicrystalline systems where, in spite of the relatively low T_g of such high-temperature polymers, the benefits to environmental resistance obtained with semicrystalline systems are driving users to study primarily these polymers. The retention of useful, although reduced, properties beyond the T_g for crystalline material, although of value and of reassurance to aerospace designers, is not apparently of primary interest because the properties exhibited beyond the T_g are inadequately competitive for the primary design case.

Although the primary interest is in semicrystalline systems, the availability of high-temperature amorphous polymers, and the recent development of even higher-temperature ones, continues, however, to intrigue the composite design engineer because, of course, the retention of properties up to these elevated temperatures is a major bonus. In contrast with the experience of a decade or more ago, where amorphous systems then available were found to be disastrously attacked by widely used paint-stripping chemicals based on methylene chloride, the environmental performance of some of the newly developed high-temperature amorphous polymers is significantly improved. Indeed, the industry itself is rethinking the wisdom behind application of chlorinated solvents for organic polymer based structures, thermosetting or thermoplastic, coincidentally with environmental concerns about such solvents. It is perhaps unlikely that the debate on crystallinity will be fully resolved until evaluation of the more advanced amorphous polymers (now becoming available) is completed.

Interestingly, the advanced composite drive is leading to the development of systems with higher operating temperature as illustrated in figure 3.

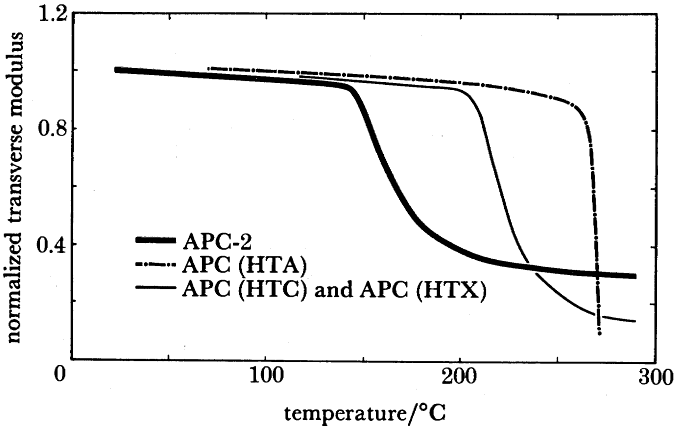

FIGURE 3. Effect of temperature on transverse modulus. (Normalized to room temperature modulus.)

3.3. *Toughness*

A major drive for the examination of thermoplastic matrices has been the susceptibility of brittle thermosetting systems to impact-initiated failure.

The response of laminated structural composites to impact calls for a new look at the traditional evaluation and understanding of matrix toughness, and studies in this area are the scene of much academic and industrial activity. Concern centres on the integrity of loaded structures in the face of locally applied impact that causes delamination of the composite structure. Such delamination may then propagate, leading to catastrophic structural failure particularly in the compressive design case. The role of the matrix in this type of damage appears to govern two quite distinct modes of failure. In the primary incident causing delamination, the matrix has a role to play in its sensitivity to failure under shear during flexing of the impacted structure. In subsequent loading, it controls the rate of propagation of damage under, for example, buckling conditions. Propagation of impact damage can arise from a variety of loading conditions, and propagation through fatigue has also been of concern.

The drive towards thermoplastics has arisen from their inherent toughness and the performance of thermoplastics systems that were first examined, such as ICI's APC2, confirmed the views of composite designers that resin toughness has a major role to play (figure 4).

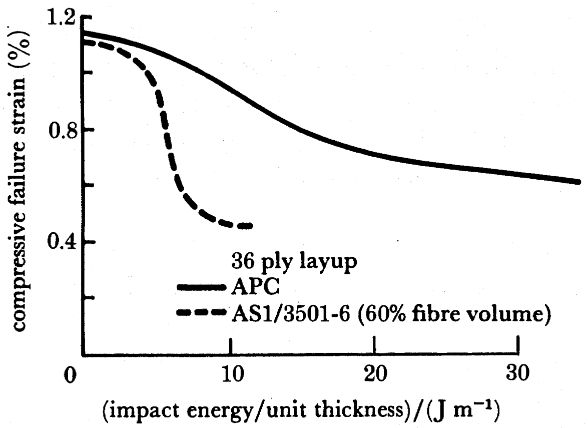

FIGURE 4. Damage-tolerance test: compressive failure strain.

Indeed thermoplastics systems set the standard for performance in this area, primarily we believe by both reducing the propagation and scale of initial damage. However, the relation between resin toughness (judged for example through fracture mechanics) and impact sensitivity is unclear and further research into the mechanisms controlling impact-initiation and propagation continues. It is certain that the inherent advantages of thermoplastics will be further tailored to yield even greater benefits in this area.

3.4. *Environment*

For applications demanding high levels of structural integrity, assurance on the results of exposure to environments commonly associated with the user industry is of real concern. Thus testing of systems in estimated 'worst-case' environments is a hallmark of the evaluation of new matrices and their composites (table 2).

TABLE 2. ENVIRONMENTAL PERFORMANCE OF UNIAXIAL APC PEEK–CF COMPOSITES

exposure for 1000 h at room temperature (non-optimized interfaces)	flex strength/MPa
datum	1410
Skydrol 500B	1243
kerosene RD 2494	1243
Esso oil ET025	1252
compressor washing fluid (water, kerosene, emulsifier)	1359

For highly sensitive structural parts, it seems unlikely that amorphous-based systems will be accepted. An option lies in combining highly crystalline systems in the outer plies of composite structures with the main structure being derived from high-temperature amorphous products. It seems likely that such 'macro composites' will be a feature of less demanding structures as design engineers recognize the flexibility offered by compatible thermoplastics systems and optimize their designs accordingly.

A key area of environmental concern is the response of the matrix and ensuing composite to water. Operating conditions for aircraft represent wide-ranging humidity and temperature environments. The degree to which water is absorbed into the structure and its effects are of major importance. This concern, driven initially by the plasticization effects of water on epoxy cross-linked resins, has led to the examination of structural performance in 'hot–wet' environments, generally citing the compressive performance as being most sensitive to matrix properties. The low water uptake of the more advanced thermoplastics and their freedom from ensuing chemical interaction is an additional drive towards their adoption, particularly when combined with higher-temperature operation. Examples of this performance are shown in table 3.

TABLE 3. ENVIRONMENTAL PERFORMANCE OF UNIAXIAL APC PEEK–CF COMPOSITES

condition	shear strength MPa[1]
dry sample	105
wet conditioned sample (95 °C in water for 240 h: water uptake ≈ 0.2 %)	110

1. Short beam flexure, 5:1 span–thickness ratio.

3.5. *Fire and smoke*

Nowhere are fire performance and smoke generation of materials of more importance than in aerospace applications. The concern covers not only flammability of materials, but also the penetration of structures by high-energy flame and the generation of both smoke and toxic by-products in the presence of fire. Of thermoplastic systems available to the composite designer, the aromatic polymer systems are superlative in this regard, and indeed it is this property which in a number of cases is encouraging their adoption (figure 5).

Interestingly, the flame penetration of thermoplastic matrix composite structures has been shown to be better than that of aluminium skins, in tests developed to compare materials for aeroengine cells.

The use of highly aromatic polymers that minimize the incorporation of flammable species or those likely to generate seriously toxic by-products, is a major consideration in the design and selection of polymers.

3.6. *Interfaces*

Although not characteristic of the matrix alone, no discussion on composites will be complete without reference to the matrix-to-fibre interface, because it is through this that load is transferred. The resistance of this interface to 'wicking' damage when subjected to hostile environments is a major contributor to successful performance. The design of interfaces promoting compatibility and the interaction with polymer chemistry will continue to be a major

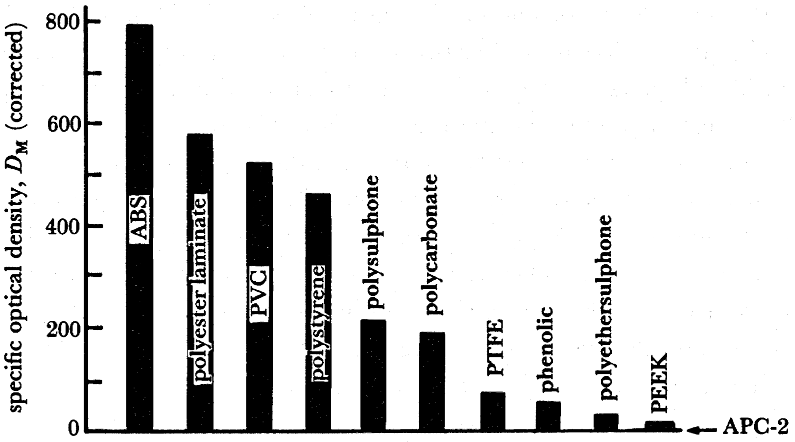

FIGURE 5. Smoke generation. Test conditions: American National Bureau of Standards smoke chamber; 3.2 mm samples; flaming condition.

field of endeavour involving a combination of chemical and physical adhesion. The fibre–matrix interaction shown in figure 6 of nucleation of crystallization in semicrystalline matrices is one example of this effect. Further evidence of the importance of such knowledge and its significance, even in the presence of a high-performance matrix, is illustrated in table 4 which shows the response of fibre composites based on polyetheretherketone to water damage and illustrates the properties of different materials interfaces.

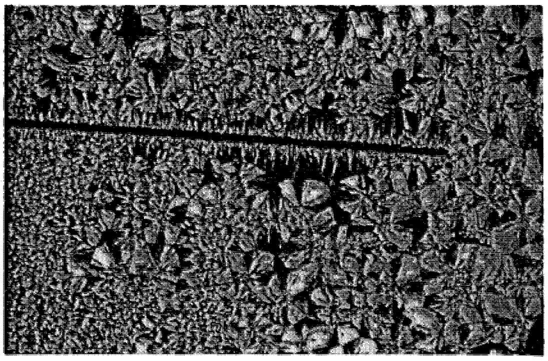

FIGURE 6. Fibre–matrix interaction of nucleation of transcrystallization in semicrystalline matrices.

TABLE 4. WATER-SENSITIVITY

	retention[1]
PEEK–carbon fibre	100%
PEEK–glass fibre (standard)	20%
PEEK–glass fibre (optimized)	40%

1. Retention of transverse flex strength after 24 h boil.

4. AROMATIC POLYMERS

The above criteria lead us to believe that thermoplastic polymers that are largely aromatic in structure will be the primary thermoplastic matrix for advanced-performance composites. Over the years, considerable research into such materials and their synthesis has been undertaken by the world's major chemical companies such as Union Carbide, ICI, Dupont and Raychem. That the sole results of this research should, until relatively recently, be a limited range of aromatic polymers, is primarily a reflection of the difficulty in synthesis of such structures and the lack of previously identified commercial targets.

Coupled with the described thermal, mechanical and environmental properties, one requires stability of the structure under the processing conditions so that fabrication can be achieved without failure of the organic linkages, while providing a processing window acceptable in practice. The retention of thermoplasticity, i.e. the ability to melt and reform, is likely to limit the use of systems to those having melting points below 450 °C, and in practical terms, probably closer to 400 °C. The requirements for use of a polymer at elevated temperature have been excellently summarized by Critchley *et al.* (1983) these are:

1. retention of mechanical properties; high softening point, high glass-transition temperature;
2. high resistance to thermal breakdown;
3. high resistance to chemical attack, i.e. oxidation and hydrolysis.

However, with regard to thermoplastics, this is perhaps incomplete because a form of 'chemical' attack occurs with solvents and fluids commonly encountered in service. These are hydraulic fluids, fuels, de-icing fluids, paint removers, etc., which may cause cracking, crazing or swelling of polymers; indeed this is almost always so with amorphous plastics but is substantially reduced or absent in crystalline polymers. Figure 7 exhibits identified structures and some key properties illustrating both existing commercial and experimental products. It can be seen that the majority of those described are crystalline; but as will be seen later, very few crystalline polymers are available commercially.

Research to achieve this attractive balance of properties at lower costs will continue, although for high-performance, low-matrix content materials, this is not a principal concern. As an

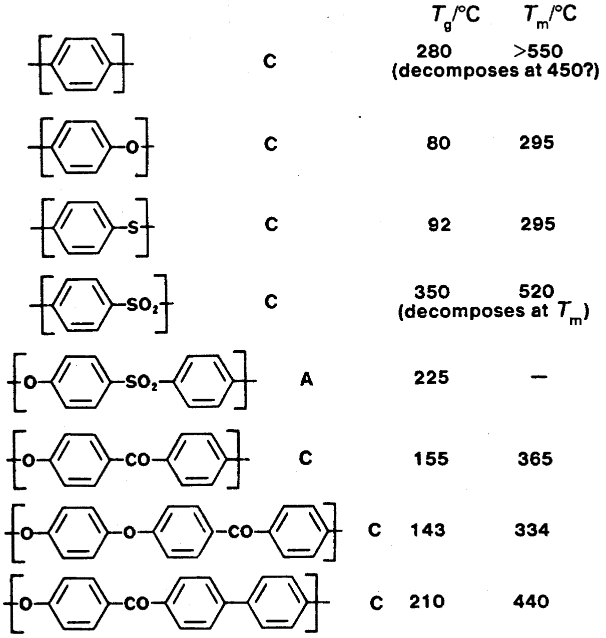

FIGURE 7. Some aromatic polymers. C, crystalline; A, amorphous.

analysis of the structure of such polymers illustrates, the relative costs are determined primarily by the routes to synthesis rather than the cost structure of the basic raw materials. From an engineer's viewpoint, such materials are little else but polymerized benzene, which offers a continuing challenge to polymer chemists and process engineers alike, albeit the difficulties should not be underestimated!

Polyphenylene, i.e. 'polymerized benzene' can be thought of as the simplest aromatic ring system and although benzene is reportedly stable up to 550 °C, polyphenylene decomposes below its melting point of 550 °C. This is a result of the imperfect or 'unclean' structures that exist in the samples so far prepared. In fact, no viable route yet exists to manufacture a pure para-phenylene structure and if one did, the polymer would remain intractable. Tractability, i.e. the ability to fabricate, is attained by introducing flexibilizing groups such as ether, carbonyl or sulphone, which are all thermally stable, fully oxidized linkages. It is perhaps surprising that, as yet, no suitable routes exist to some of the simplest structures, such as polyphenylene-ether or polyphenylene-sulphone. In the latter case, arguably this is not of serious concern because the experimental products have exhibited decomposition at the melting point and thus the material has no use as a thermoplastic. Unsubstituted polyphenylene-oxide (i.e. *not* the material incorporated in Noryl) is an attractive polymer but has a rather low T_g, a feature because of the presence of the extremely flexible ether link. In any event polyphenylene sulphide, sold by Phillips, appears to fill this particular slot adequately. The more useful materials contain combinations of 'ether' and other groups. Polymers with the electron-withdrawing ketone and

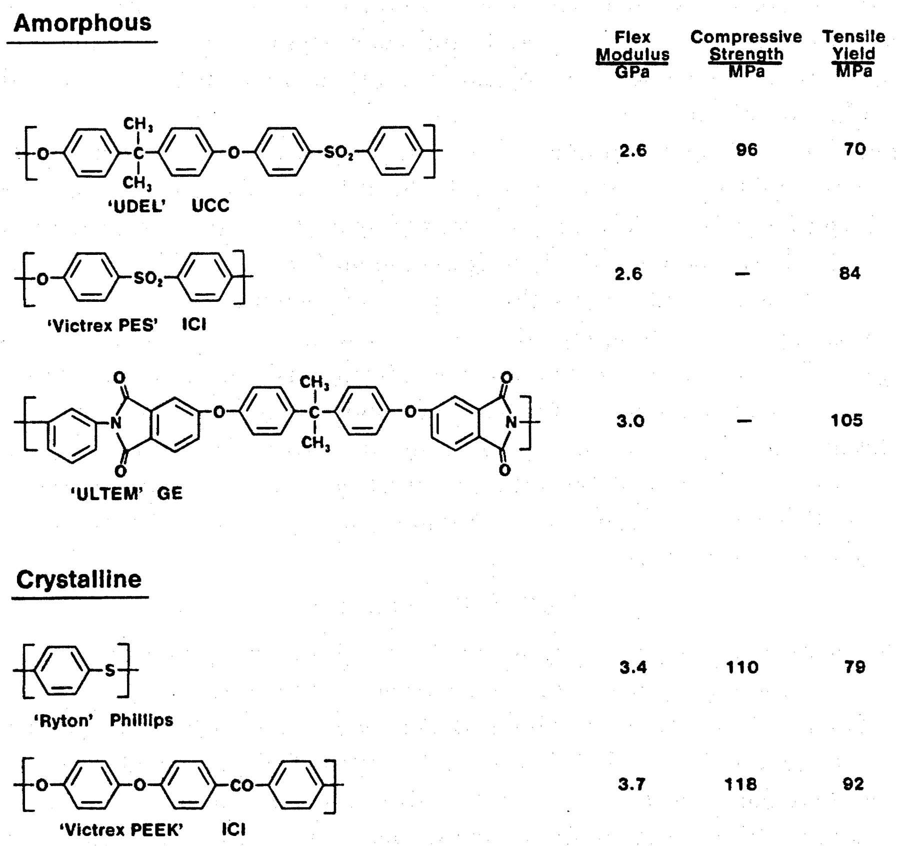

FIGURE 8. Commercial aromatic thermoplastics.

sulphone groups can be prepared by nucleophilic or electrophilic processes. For the former the ether linkage is formed, whereas in the latter, the ketone or sulphone linkage is closed during polycondensation.

4.1. *Commercial polymers*

A number of commercial polymer structures exist, the identifying difference being the linkages between adjacent aromatic rings, which in turn, of course, yield the inherent properties and define processability (figure 8).

All of these have been identified as of interest at some stage for structural composites. The field of commercially available aromatic crystalline systems is, to date, much more limited, although activity in a number of major chemical companies is reported, supporting our contention as to the value of high-temperature semicrystalline aromatic resins.

5. FABRICATION

The availability of simple fabrication processes, not involving the control of chemical reaction as in cured thermosets, supports the use of thermoplastics. A brief survey of such techniques may be useful here. Although a number of viable techniques has been demonstrated both by aerospace companies and materials producers, the options available to the composite engineer have almost certainly have not yet been fully explored, and the advantages to be gained have yet to be fully demonstrated. The competition between optimum material design on the one hand (where, of course, the use of composites produces a further degree of freedom over the use of metals through integrated materials and component design) and the most economic routes to fabrication on the other, is a subject that continues to require close interaction between designers and materials suppliers.

This is best illustrated if we examine two extremes that surround this discussion, the high-rate forming of prelaminated sheetstock against the local layup of single plies oriented locally to maximize design flexibility, allowing, for example, specialized structures such as the forward swept wing. The debate between the two schools, identified as the 'black-aluminium' against the 'tape-layers' factions, illustrates the scope of opportunities and choices available. In practice, a wide range of techniques will be used, of which each will find their natural place in the balance of properties and economics. The advent of advanced thermoplastic composites has begun to redraw the lines of activity between designers, convertors and materials suppliers, primarily because such materials have opened up intermediate phases of material supply and fabrication which were less available with thermoset systems. Techniques under study for the fabrication of thermoplastic composites originate in the metals, thermoplastics, and the thermoset composites industries.

5.1. *Filament winding*

The concept of winding pre-impregnated thermoplastic composite tapes involving rapid heating, consolidation and quenching have been demonstrated by a variety of heating techniques. Potentially one of the most interesting may be the use of laser energy. Thermoplastic composites offer advantages beyond simply the ability to wind completed structures in a single operation without the need for post cure, but also as a route to non-geodesic winding. The filament winding of thermoset composite components involving surfaces of revolution other than simple cylindrical shapes is well known and the filament winding of massive aerospace components and, on an experimental basis, the fuselage of light aircraft, has also been reported. The concept of thermoplastic filament winding offers a highly productive route to complex components.

5.2. *Tape laying*

As a route to the automated manufacture of structural aerospace components, where material properties can be varied locally within the structure by the orientation and numbers of plies of a uniaxial tape, tape placement is an area where significant sums of money have been invested over the years for thermosetting composites. Development of this technique for thermoplastics, may lead to the demise of massive-scale autoclaves for post curing, and is receiving development attention. Simple thermoplastic composites have been tape layed for experimental purposes. The technique is believed to be of major value for the manufacture of the most sophisticated and larger-scale structures.

5.3. *Rubber forming*

The use of metal tooling, forming preheated thermoplastic composite sheet against rubber; a technique borrowed from the sheet-metal industry, has demonstrated the ability to form simple shapes.

5.4. *Hydroforming*

This technique, which is a more sophisticated development of rubber forming, is again based on preheating and has yielded a range of deeply shaped structures including experimental parts now used in flight testing.

5.5. *Superplastic diaphragms*

Cooperation between ICI and Superform, a subsidiary of Alcan, led to the development of an ability to form deeply contoured and well-controlled shapes from laminates consisting of multiple plies of uniaxial materials in chosen orientations. The technique has shown itself applicable to large structures (figure 9); facilities exist for fabrication both in the U.K. and

FIGURE 9. Superplastic diaphragm formed component.

in Riverside, California. It is clear that further developments of the technique are feasible including the combined forming and assembly of substructure.

5.6. *Rolling*

Conceptually, the rolling of preheated composite sheet, with similar technology to the sheet metal industry, has been shown to be feasible in principle; and this includes the ability to produce 'circled' linear structure, i.e. curved linear shapes.

5.7. *Pultrusion*

By using a variety of feedstocks, consolidation of thermoplastic structures in heated dies has been demonstrated either through work in the aerospace majors or through composite fabrication companies.

5.8. *Sheet laminates*

The compatibility of various material forms, with the fabrication techniques described, illustrates the manner in which these materials are stimulating new ideas. The composites industry has highlighted the use of impregnated woven fabrics as a route to 'broad goods'. Such fabrics offer the ability to lay down large surface areas relatively economically, although the weaving of high-performance fibres has a significant cost. In turn, their use has led to the demand for weaves promoting maximum formability. Although loss of properties as a result of the fibre deformation arising in such structures is recognized, the balance of economic advantage has led to their continued use. The ability to provide prelaminated thermoplastic sheet materials of non-woven multi-plies could be an important economic option. Interply slippage and rotation in the molten state has shown that complex shapes, without the constraint imparted by weaves, can be achieved even though, of course, fibre extension is not feasible.

5.9. *Matrix stability*

A feature of all these fabrication techniques requires processing above the melting point and, in a number of cases, over periods of several minutes. Clearly, such processes are most attractive when conducted in air rather than when requiring the special provision of inert atmospheres, illustrating the importance of matrix stability under the specified processing conditions. The thermal stability of these aromatic advaced thermoplastic matrices is the subject of study, and evidence exists that systems based on aromatic polymers are satisfactory in this area.

6. PROCESSING SCIENCE

A preoccupation of the composite engineer is the precision placing of fibre because quite modest misalignments of a few degrees under critical loading conditions can result in dramatic reductions in properties. At the same time, the presence or absence of fibre in a ply caused by errors in placement are also of concern. The use of high-rate forming techniques has significant economic potential, but it is necessary for the designer to have complete confidence in the process control of the fabrication technique, together with an ability to predict local properties. To this end, the examination of these processes to project the resulting fibre placement, the limiting processing conditions and the component forms will be a major preoccupation of industry in conjuction with academia. Examples of such cooperation are research programmes now being conducted at the Universities of Nottingham, Aberystwyth and Delaware into the flow modelling and prediction of fibre placement as a result of thermoforming.

7. SUMMARY

In conclusion, the reasons for interest in advanced thermoplastic composites have been outlined and future opportunities for advancement in their science and technology have been indicated. This advancement will include the design of aromatic polymer structures and routes to their synthesis. When combined with interface science, in conjunction with advanced reinforcing fibres, a range of materials emerge that will find application in demanding and sensitive structural environments. Further development in 'new' fabrication routes will lead to improvements in the economics of composite structure composites, but for critical industries, this will require significant research effort in fabrication science to define the process interactions.

The achievement of major commercial activity in these new classes of materials not only provides an opportunity, but demands cooperation and integrated activity over a wide range of science and technology including chemistry, process engineering, materials and interface science and fabrication–production engineering through to structural design.

REFERENCE

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Discussion

M. BHATT (*Department of Materials, Queen Mary College, London, U.K.*). During Mr Belbin's paper, he claimed that he did not believe in macrocomposites, but did not define what he meant by a macrocomposite. Would he please define the term and explain why he does not believe in these macrocomposites?

Also, so far we have had papers that concentrated on glass and carbon-fibre reinforcements for thermoplastics. Would he comment on alternative reinforcements, such as beads, or laminae, and to speculate on other materials that may be suitable for reinforcement in any form?

G. R. BELBIN. My definition of macrocomposites covers combinations of various differing laminae materials into a single laminate or structure. Thus is it possible to produce laminates whose properties spectrum provides an optimized combination of differing individual laminae, each laminae being chosen for a specific property contribution. I illustrated the point in my paper by proposing the use of high-temperature amorphous structures with polymer based cores protected by environmentally resistant crystalline outer plies.

I did not mean to indicate lack of personal belief in the concept because my own view is that such optimization is of real value but that the aerospace industry did not see this as a solution to the specific problem of environmental resistance of amorphous systems.

Responding to the second question, the emphasis on fibre reinforcement of course stems from the dramatic property gains to be achieved from aligned-fibre reinforcement and, of course, the field is wider than glass or carbon covering aramid alumina and the high-performance inorganic fibres each targeted on the achievement of specific property effects at a price.

The use of beads or laminae are generally directed at lower levels of performance or the generations of specific effects such as syntactic foam for beads.

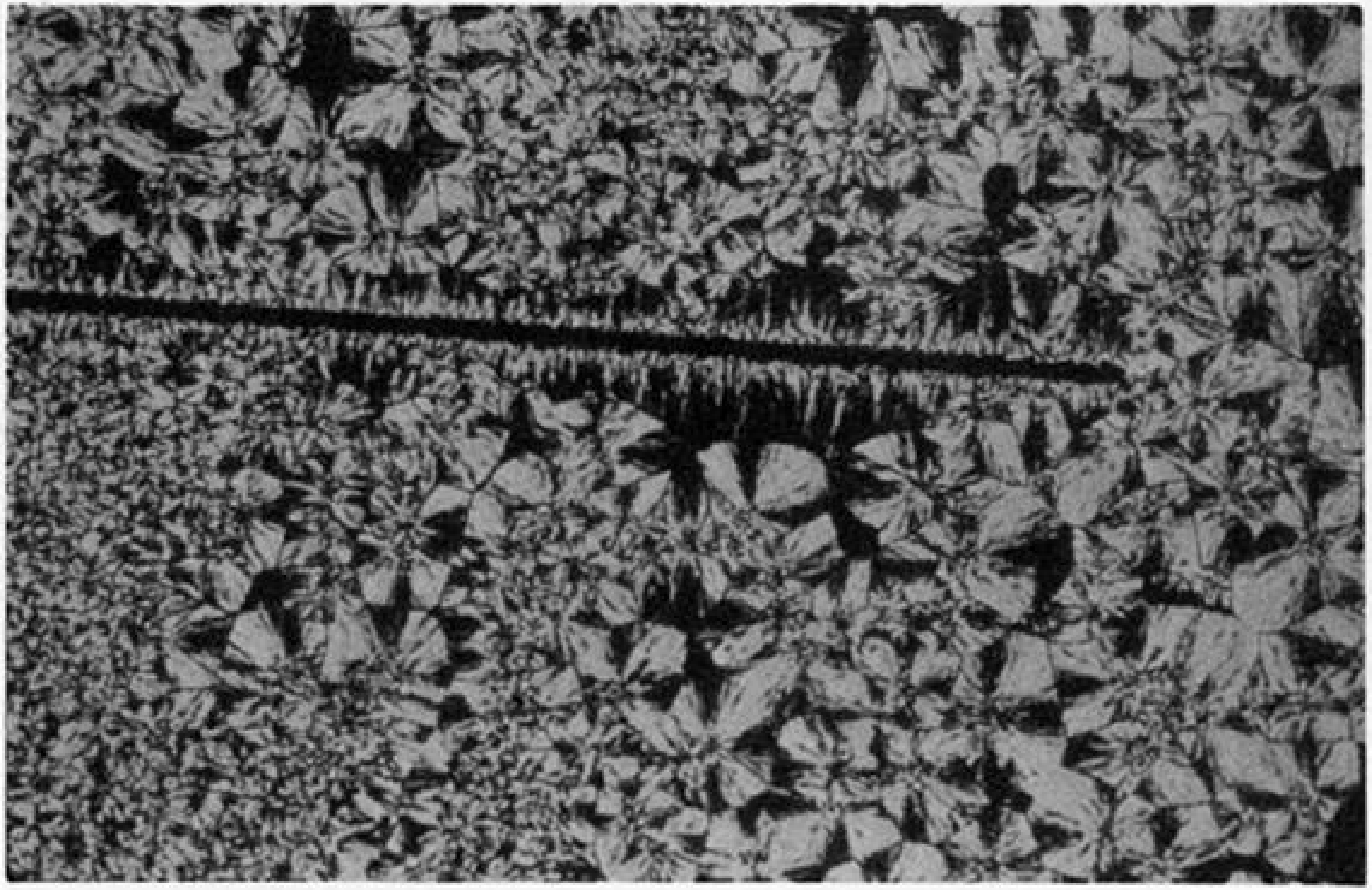
S. F. Bush (*UMIST, Manchester, U.K.*). Mr Belbin appeared to concentrate on essentially thin-section applications of APC; notably those that could be obtained from APC tapes and mats. However, it is understood that even with its high melting point PEEK can be injection moulded. Foam injection moulding is, in general, an attractive option, particularly for polymers that are relatively amorphous, as some variants of APC (for example the HTC referred to) apparently are. To what extent is the APC exploitation programme concerned with injection moulding?

Is Mr Belbin able to indicate the broad ways in which the variants (HTX, HTC) achieve their higher working temperatures? Are they, for instance, branched chains, or stiffer chains of the basic PEEK type, or essentially new basic repeat units?

G. R. Belbin. The injection moulding of short-fibre-reinforced thermoplastic polymers is, of course, well established, and PEEK is no exception where a wide range of applications is now established commercially, including the use of carbon fibre reinforced grades.

Added property benefits, including impact strength and creep performance, arise from the moulding of longer-fibre-reinforced polymers, where those reinforced grades are correctly prepared. Such products are exemplified by ICI's 'Verton' range, and although commercial activities are today concentrated on grades of lower property–price, development products based on PEEK and C.F. are available. APC is targetted on the maximizing of structural properties obtained by the high packing density achievable with aligned fibres, and by the control of properties through defined fibre orientation. The randomizing effects achieved during injection moulding do not lend themselves to the achievement of the degree of absolute performance or control.

Variants of the aromatic polymers developed for APC, to achieve higher-temperature performance (HTX, crystalline; HTA, amorphous; HTC, crystallizable) are primarily based on the incorporation of stiffer chains and rearrangement of units to provide or control the crystallization behaviour of the resulting polymer.



IGURE 6. Fibre–matrix interaction of nucleation of transcrystallization in semicrystalline matrices.

IGURE 9. Superplastic diaphragm formed component.