

## **8. Summary, Conclusions and Recommendations**

This report has examined the evolving field of high performance thermoplastic resins and their composites. Thermoplastic polymers of various chemical families having the potential to be used as matrix for composites in aircraft structural applications have been identified and presented. The chemical families include polyketones, polyarylene sulfides, polyamides, polyimides, polysulfones, liquid crystalline polymers, polybenzimidazoles and polyphenylquinoxalines. Discussions on the performance of neat and continuous fibre reinforced thermoplastic resins in terms of their chemical properties, room temperature and elevated temperature mechanical properties, damage tolerance, environmental and chemical resistance and fatigue and creep behavior have been provided. The interrelationships between morphology and properties of semi-crystalline thermoplastic composites have been addressed as well as the factors influencing the morphology. The techniques to combine fibres and matrix, to produce laminates, to form three-dimensional parts and to join thermoplastic composite parts have been described. Many conclusions have been reached and the ones considered to be the most important are provided below along with recommendations for future research and development work.

### **8.1 Neat Thermoplastic Resins**

There is considerable interest in advanced thermoplastic composites in the aerospace community. Already, an interesting choice of these novel materials is available in the marketplace for use as matrices for composites in aircraft structural applications; and others are expected to emerge. In general, high performance neat thermoplastic resins exhibit mechanical properties comparable to those of thermosets but they are characterized by outstanding toughness, higher ductility reflected by high tensile strain to failure and lower moisture absorption. In general, they exhibit good temperature capability as they possess high glass transition temperature ( $T_g$ ). But the very high desired  $T_g$  leads to high melt viscosity which renders the complete impregnation of the fibres by the matrix difficult and thus impeding the availability of some thermoplastic resins in the prepreg form. The development of very flowable high performance thermoplastics that possess enhanced elevated temperature performance is highly desirable and should be investigated.

### **8.2 Morphology**

The morphology of semi-crystalline thermoplastic polymers is a fundamental issue. It is important to know how mechanical properties are affected by the morphology of the polymer and how the morphology of the matrix of the composite of interest is influenced by processing conditions. The effects of exposure to solvents encountered in aircraft applications on the morphology of semi-crystalline thermoplastics should be investigated. Special attention has to be paid to non-uniform heating during the processing of semi-crystalline

thermoplastic based composites, especially in the cases of thick and tapered laminates or during a repair process using welding techniques.

### **8.3 Thermoplastic Composites**

In general, mechanical properties of thermoplastic composites are similar to those of thermoset composites. Thermoplastic composites also perform very well at elevated temperature but additional data concerning the retention of properties at elevated temperature and under combined hot/wet conditions are sorely needed, especially the matrix dominated properties. Thermoplastic composites exhibit lower shear and compression strength than those of thermoset composites. Studies should be undertaken to better understand why they are weaker and how these properties can be improved. It seems that fibre/matrix adhesion and fibre distribution, fibre alignment and shear stability may be very important contributing factors to the compressive response.

Relationships used to predict the composite properties of thermoset composites from their neat resin properties may not be applicable to thermoplastic composites. Correlations enabling prediction of thermoplastic composite performance from the neat resin evaluation should be therefore investigated.

One of the main advantages of using thermoplastic composites in aircraft structural applications over thermoset composites is their markedly superior damage resistance and tolerance. Thermoplastic composites exhibit toughness values up to ten times higher than those of thermosets. The delamination behavior of thermoplastic composites as demonstrated by ICI's APC-2 (PEEK) composites is different to that of thermoset composites. APC-2 exhibits non-linear viscoelastic behavior which is rate dependent. Epoxy resin does not plastically deform to the same extent as PEEK resin.

Thermoplastic composites seem to perform reasonably well in fatigue but their creep resistance is probably lower than thermoset composites. However, the few data on fatigue and creep properties of current thermoplastic composites are insufficient to conclude whether or not thermoplastic composites offer any advantages over epoxy based composites.

From the limited data available, the resistance of thermoplastic composites to thermal cycling and radiation encountered in LEO and GEO orbit appears to be comparable to that of thermoset composites. Further work is needed to assess the potential of thermoplastic composites for use in space structures.

## 8.4 Processing

There are major benefits in processing thermoplastic composites compared to thermoset composites including the unlimited shelf life, generally short processing times (some require long and elaborate processing cycles with the evolution of volatiles) and the ability to be remelted and reprocessed. The main drawbacks are high melt viscosity, high processing temperature and the lack of tack and drape of most prepregs.

The interfacial adhesion between fibres and matrix is generally lower than that observed for epoxies. Fibre treatment used for thermoset polymers to promote adhesion to the fibres may be inappropriate for thermoplastics. Means to improve the interfacial adhesion and their effects in controlling mechanical properties should be investigated.

Residual stresses are an important issue when processing high performance thermoplastic composites since they are likely to be higher than those found in thermoset composites due to the higher processing temperatures. Care should then be taken regarding void formation and matrix cracking due to residual stresses formed during processing.

Some of the processing routes followed to produce high quality thermoplastic composite parts are well established as they are used with thermosets or borrowed from metal forming technology while other techniques are new and still require improvement. The effects on mechanical properties of the techniques used to combine fibres with thermoplastic matrix as well as the techniques used to produce consolidated laminates should be investigated further. Major effort should be placed on the development of cost-effective processes to offset the high cost of raw thermoplastic material. Automated processes such as tape laying, filament winding and pultrusion are very attractive processing techniques from an economical point of view.

Thermoplastic composites can be machined by conventional means, parts with defects can be reprocessed and scrap material can be reused. However, the effects of processing history on morphological structure, chemical and mechanical properties should be more thoroughly investigated.

## 8.5 Joining

A wide range of techniques to join thermoplastic composites is available. The composites can be mechanically or adhesively joined and due to their ability to be remelted, they can be joined by local consolidation at the joint interfaces using a variety of novel techniques. These new promising welding techniques are still in an early stage of development and need further improvement, but they may provide new opportunities in the repair of thermoplastic composite structures especially for aeronautical applications.

## 8.6 Aircraft Applications of Thermoplastic Composites

The replacement of metallic and fibre reinforced thermoset components with thermoplastic based composites is now occurring. Even though applications of thermoplastic composites in primary and secondary aircraft structures are becoming increasingly common, they have not yet received wide acceptance. The inertia in utilizing them in aircraft structural applications is attributed mainly to the unanswered questions concerning their fatigue and creep behavior and poor compression properties, the lack of processing experience, the high cost and the limited data available. It is obvious from this review that more research on thermoplastic composites is needed. More data have to be generated, especially for other thermoplastics besides PEEK and PPS that deserve attention.

Each thermoplastic matrix has its own advantages and disadvantages; the final selection depends mainly on the application, particularly in terms of stress or strain involved, time under load, environmental conditions, solvents involved and costs. For higher temperature applications, such as supersonic aircraft, polyimides and polybenzimidazoles are promising choices, but there is a draw-back of difficult processing. If moisture resistance is required, polyamideimides should be avoided. If exposure to aircraft fluids is likely to occur, then polysulfones should be eliminated. For very high toughness requirements, all thermoplastic resins are suitable except polyphenylene sulfide which has  $G_{Ic}$  toughness values similar to the thermoset ones. Overall the polyketone family is a judicious choice as it offers well balanced properties. Except for their outstanding toughness, the mechanical properties of polyketones are not exceptional but they are at least comparable to conventional thermosets. They exhibit excellent solvent and moisture resistance and they have good melt processability. Amongst the thermoplastic polymers in the polyketone family, ICI's polyetheretherketone polymer (PEEK) has the advantage of an extensive database established by the manufacturers, the scientific community and aircraft designers and engineers, however the latest polyketones exhibit higher Tgs than the well known PEEK.