PMI Foam Cored Sandwich Components Produced by Means of Different Manufacturing Methods

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Abstract: The paper introduced the structural applications with PMI (Polymethacrylimide) foams in sandwich components for rotor craft, launching vehicle and civil aircraft and discuss some typically used manufacturing methods, such as *e. g.* in-mould pressing, autoclave curing and resin infusion. The advantages of foam-cored sandwich design versus honeycomb-cored design will be discussed, focussing on manufacturing costs.

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1 Properties of Rigid Foam Plastics

1.1 Mechanical Properties at Room Temperature

Logically, the suitability of foam core materials for a particular sandwich application depends on the structural requirements resulting from the design calculation. If we compare the mechanical properties at equal densities, it becomes obvious that PMI foams offer outstanding properties (Fig. 1 and Fig. 2).

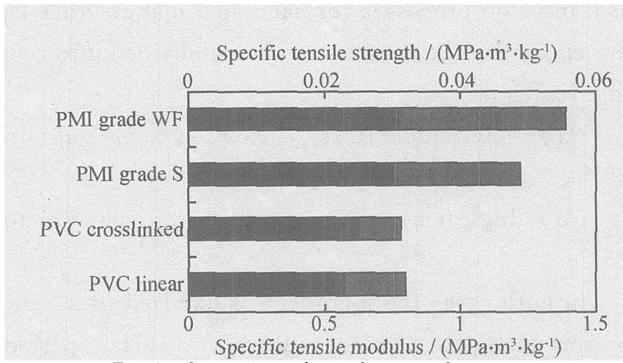

Fig. 1 Comparison chart of various foam specific tensile strength/modulus at room temperature

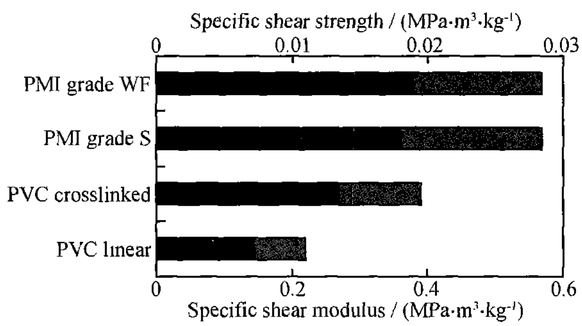

Fig. 2 Comparison chart of various foam specific shear strength/modulus at room temperature

1.2 Mechanical Properties at Elevated Temperature

In addition to the mechanical properties at room temperature, the dynamic shear modulus *vs.* temperature curve shall be used to discuss the thermo mechanical properties, referring to structural integrity of a sandwich component when exposed to elevated temperatures (Fig. 3).

It can be concluded that only the family of PMI foams visualized by a yellow band, can serve as a reliable sandwich core material at temperatures above 130℃. A significant decrease in performance first sets in at 180℃.

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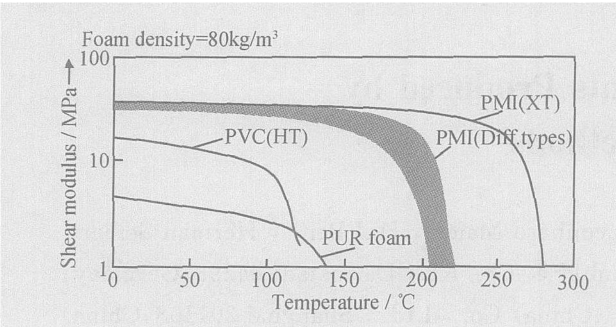

Fig. 3　Dynamic shear modulus of different rigid foam

Cycle 1: 125℃/0.3MPa/2h		Cycle 2: 180℃/0.7MPa/2h	
Type of foam	Creep/%	Type of foam	Creep/%
PU	> 12	PU	Not applicable
	Material collapsed	PVC (HT grade)	Not applicable
PVC (HT grade)	10	PMI (WF-HT)*	3.5
PMI	1.5	PMI(WF-HT)**	1.5

* HT: material heat-treated, 130℃/2h, 190℃/48h

** : density 110 kg/m³

Advanced RTM process using *e. g.* Hexcel's RTM 6

Injection	Post-curing temperature	Foam type	PU and PVC	PMI (WF grade)
~ 0.6MPa/180℃	180℃	Creep in %	Not applicable	1.5

2　Processing Ability of Rigid Foams

Today's in-mould pressing, autoclave cure and resin infusion processes for sandwich manufacture using epoxy matrix systems can be subdivided into two major categories:

(a) low-temperature curing systems up to 125℃;

(b) high-temperature curing systems up to 175℃.

In both cases the foam core is exposed to a temperature load plus a pressure load for a certain period of time. Thus the creep behaviour of the foam is the main point of interest for the manufacture. In the case of advanced resin infusion process using mono-component systems such as RTM 6, the foam core must withstand high injection-pressure (up to 0.6 MPa) and high injection temperature (up to 180℃) loads during the entire injection process.

Table 1　Suitable foams for different prepreg resin systems

Resin/Prepregs	Temperature/℃	Pressure/MPa	Foams
Polyester	RT	–	Nearly all
Epoxy	RT	–	Nearly all
Low pressure epoxy prepregs	> 80	–	PVC(HT), Rohacell
Standard epoxy prepregs	125 ~ 175	0.3 ~ 0.7	Rohacell
Bismaleinimid	190	0.7	Rohacell

A test series carried out at Röhm GmbH to evaluate some typical foam plastics in a density of 80 kg/m³ was concluded with the following results:

3　Matched Mould Co-curing Procedure

In case of matched mould manufacture of rotor blades, the cost saved by using a foam core instead of a honeycomb core. The reasons are ease of meaning the PMI foam core and a significant reduction in tooling and manufacturing costs. The honeycomb version requires six basic operations:

Shaping of first contour, lay-up and cure of lower skin to the shaped core, shaping the opposite core contour lay-up and cure of the upper skin, assembly and lay-up of procured details and final cure of the component.

The single-cure procedure of the foam cored version consists of only 3 steps:

Shaping of the core, assembly and lay-up of all details and final cure.

It is easy to see why this particular manufacturing method was so successfully applied to the manufacture of helicopter main rotor blades. The thermo elastic behaviour and excellent creep compression resistance of the PMI foams were the decisive factors for using them as "active" mandrels in the matched mould curing process development by WESTLAND engineering and Degussa. Slightly oversized foam cores provide a sufficiently high and constant level of internal pressure, perfectly consolidating even very thick prepreg layers and guaranteeing and extremely low void content in the laminate. This particular manufacture method is highly cost-effective and reliable.

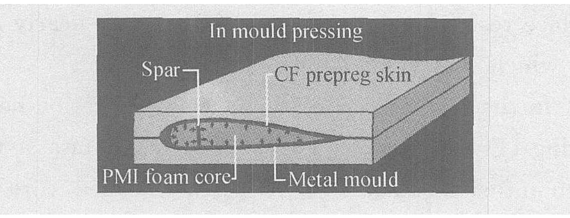

Fig. 4 Matched mould processing method

The initial change from the old metal blade design to composite blades was prompted by the wish to solve corrosion problems and the demand for increased performance and service life of the blades. A manufacturing method using PMI foam cores as an "active" mandrel and structural member of the sandwich component was developed in close cooperation between a major European helicopter manufacturer and the ROHACELL engineering team. This technology is well known as the in-mould pressure process. During the closed-mould curing process, the thermoelastic behaviour of the foam core provides internal pressure, perfectly consolidating even massive prepreg layers against the mould surface. Owing to their excellent creep compression resistance, such foam cores can provide a very high and constant level of pressure. In-mould pressures of up to seven bars can be reached and maintained during a two-hour cure cycle. The desired peak pressure can be adjusted to precisely meet the gel point of the epoxy prepreg. The superior mechanical properties of the foam improve buckling resistance of the mostly very thin U-spars used in the blade design. Thanks to their outstanding fatigue behavior, which is second to none among rigid foams, PMI foams withstand the high dynamic loads to which the rotor blades are exposed during their service life.

By using the PMI foam-cored design, the service life of rotor blades was increased from approximately 400~ 500 flight hours for the initial metal blade, to more than 10, 000 flight hours today. A detailed study carried out by BELL concluded that a PMI foam-cored tail rotor blade costs only about 20 per cent as much to manufacture as the honeycomb-cored version. This is because the foam core makes it possible to introduce a single curing process, whereas the honeycomb core requires several curing and bonding operations. In addition, machining of the foam core is much easier, and up to ten times higher feed rates are possible. PMI foam cores have been successfully introduced in many major blade programs. The main blade of WESTLAND's EH101 helicopter is probably the most impressive example. The length of the blade is approximately 8.5 metres. Eurocopter makes intensive use of PMI foam cores for their range of helicopters.

For the match mold co-curing technology, the foam oversize rate of the foam material is got with the simulation test under the curing condition (temperature and pressure curve) of the prepreg.

4 Autoclave Co-curing Procedure

At present, the prepreg autoclave method is primarily being used for the manufacture of high quality composite components since it provides a very high and reproducible component quality while requiring a moderate investment of tools. The high component quality is attained by compacting the prepregs (resin impregnated, continuous fibre products), in the autoclave. Simple tools are required because only single-sided supporting tools are needed which have a flexible vacuum cover.

If we focus on the manufacture of aircraft components, mostly NOMEX and aluminum honeycombs are used as the core material. They offer excellent strength-to-weight and modulus-to-weight ratios.

On the other hand, the non-isotropic and open-cell character of honeycombs causes some problems during core shaping and curing. Honeycombs do not withstand lateral forces/pressures and tend to collapse during core shaping and sandwich cure. They do not fully support prepreg layers during cocuring operations, which results in surface imperfections and zones of poor laminate consolidation and fiber disorientations. Another major problem is extensive moisture absorption and corrosion, which limits the performance of the component and caused increased expenditure for repair and higher service lift costs.

For these reasons, suitable rigid foam cores based on PMI have been utilized in manufacturing sandwich components for aerospace components for quite some time now. This includes secondary structures as well as primary structures for state-of-art aircraft.

PMI foam cored sandwich structure is firstly considered in the composite payload fairing for the Delta 2. The goal for the new development was cost reduction in the manufacturing process as well as in the assembly of the fairing. PMI foam was used as a bi-functional core serving as the mandrel and as a structural member of the sandwich contributing to buckling resistance. The decision was prompted by the fact that PMI foam can easily be thermoformed to even very complex geometries such as the nose section of the fairing. This makes it possible to implement a simple male tool plus a cost saving lay-up and cure procedure. Prepreg for the inner skin of the component it laid up first, followed by the precisely thermoformed patterns of the PMI foam being the mandrel for the lay-up of the outer prepreg skins. The entire lay-up is vacuum-bagged and co-cured at 175℃ in one shot.

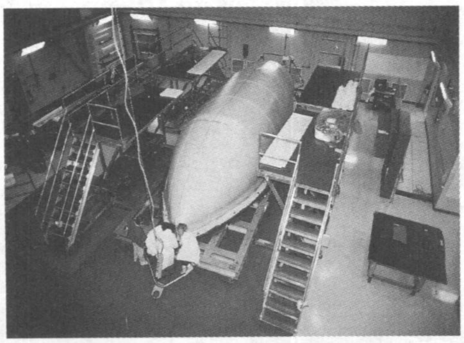

Fig. 5 Fully bagged half fairing Delta 2

5 Resin Infusion Procedure[1, 2]

The resin infusion method has become established in the past few years as an alternative to the prepreg technology. In this method to fabricate the sandwich structure, a cost-effective and nonimpregnated fibre perform and foam core is placed in a massive mould to which a low-viscous resin system is injected under pressure.

Due to the close-cell structure of the PMI foam, it is widely used in the sandwich structure with resin infusion technology. With the latest development, PMI foam cell size can be customized so that the foam surface resin absorption can be reduced to nearly zero, which reduce the sandwich parts weight.

In the Gulfstream G 150, a new generation belly fairing (Fig. 6) realized by means of vacuum assisted resin infusion (VARI). A pre-net-shaped core of PMI foam is precisely thermoformed to the required contour. In the next step dry reinforcing material is stitched to the core making a ready-to use assembly with is easy to handle (Fig. 7). The assembly is put on the female tool and is vacuum bagged. Resin is infused by means of vacuum suction and the part is post-cured after the injection process has been finished. The rigid foam core acts as a mandrel, carrying the dry reinforcement and is also a structural member of the sandwich design. The parts produced by the low-cost VARI processing have excellent surface finish and the skins have a very high fiber volume fraction. (Fig. 8 and Fig. 9).

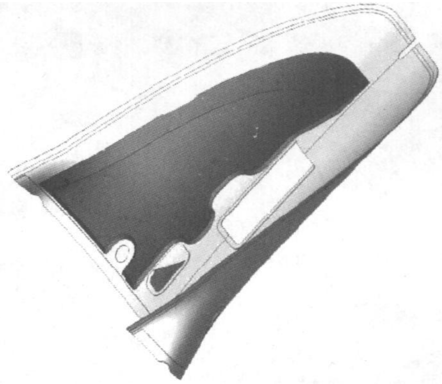

Fig. 6 Design of the belly fairing

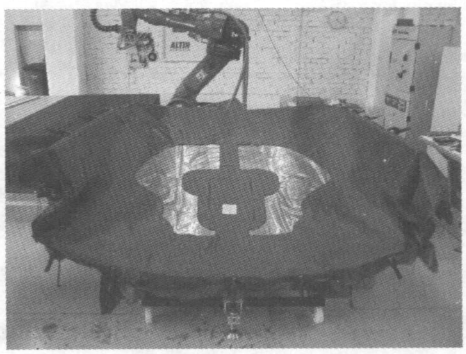

Fig. 7 Foam with stitched-on fabric

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good sign for high toughness and thus for the high impact damage resistance. It is also believed that the two-component films help to facilitate the spinodal decomposition and coarsening process, leading to the granular structure. However, an intensive investigation to this structure-property relationship is certainly needed.

3 Conclusion

In conclusion, in terms of compression after impact (CAI) behavior the *Ex-situ* concept has successfully been demonstrated for BMI 6421 / PAEK laminated graphite systems, particularly if the two-component films of a specific composition ratio of 60∶40 were periodically interleaved.

Acknowledgements

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References:

[1] AN Xue-feng, TANG Bang-ming, YI Xiao-su, et al. Toughness improvement of carbon laminates by periodic interleaving thin thermoplastic films [J]. Journal of Materials Science Letters, 2002, 21: 1763- 1765.

[2] YI Xiao-su, AN Xue-feng, TANG Bang-ming, et al. *Ex-situ* formation of periodic Interlayer structure to improve significantly the impact damage resistance of carbon laminates [J]. Advanced Engineering Materials, 2003, 5: 729- 732.

[3] LONG Wei, XU Ya-hong, YI Xiao-su. Preliminary study on resin transfer molding of highly-toughened graphite laminate by *ex-situ* method [J]. Journal of Materials Science, 2004, 39: 2263- 2266.

[4] YI Xiao-su, AN Xue-feng. Effect of interleaf sequence on impact damage and residual strength in a graphite/epoxy laminate [J]. Journal of Materials Science, 2004, 39: 3253- 3255.

[5] YI Xiao-su, XU Ya-hong, CHENG Qun-feng. A method to significantly enhance the toughness of BMI based laminated system [P]. Chinese Patent in pending, 2005.

[6] ANON. Handbook of polymer matrix composites materials (in Chinese) [M]. Beijing: Beijing Chemical Industry Press, 2004.

[7] ZHANG H, CHEN T, YUAN Y. Chinese Patent : CN85. 108 751, 1985.

[8] HOGG P J, PRICHARD J C, STONE D L. A miniatured post-impact compression test [C]. Private communication, 1999.

[9] INOUE T. Reaction-induced in phase decomposition in polymer blends[J]. Progress in Polymer Science, 1995, 20: 119- 153.

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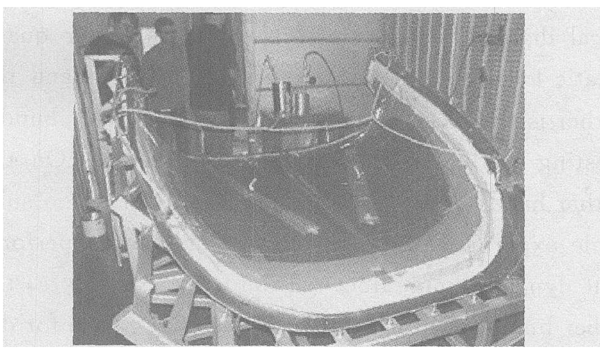

Fig. 8 Infusion procedure

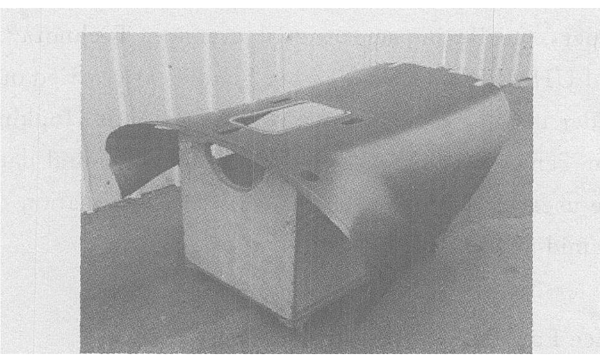

Fig. 9 Cured and trimmed part

6 Conclusion

In conclusion, it can be state that high performance PMI foams meet the demands of the match mould press, autoclaving and any kind of resin infusion processes.

The excellent creep compression resistance and outstanding temperature resistance of PMI foams make it possible to use them for all common cure cycles. Post-curing temperatures up to 225 ℃ are allowed. PMI foam core can be used with cost effective cocuring processing technology and it is easy to be shaped.

References:

[1] HERMANN SEIBERT. Recent application for PMI foams in aerospace sandwich structures[A]. RP Asia Conference and Proceedings[C]. Bangkok: Elsevier Advanced Technology, 2005.

[2] IAI commercial aircraft croup: ALONIM J, ARNON E, DAVID A, et al. Development of a business jet component by resin infusion using a stitched preform[A]. SAMPE Conference[C]. Israel, 2005.