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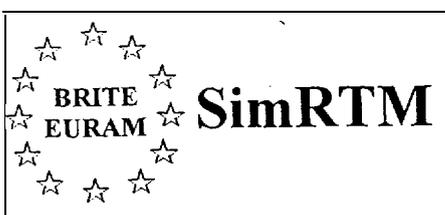
PROJECT NUMBER: BE5477-92

TITLE: Simulation of the Resin Transfer Moulding Process for Efficient
Design and Manufacturing of Composite Components
(SimRTM)

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PROGRAMME:

Simulation of the Resin Transfer Moulding Process for the Efficient Design and Manufacture of Composite Components (SimRTM)

BRITE-EURAM Contract Number BRE2/CT/92/0227
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ABSTRACT

This document is the publishable synthesis report of the CEC funded project BE5477-92 (BRE2/CT/0227) the aim of which was to improve the state of the art and design methods utilised, within Europe for components manufactured using resin transfer moulding (RTM). This was achieved by the interaction of data and experience produced from a four main tasks:-

1 Material Characterisation - this involved the measurement of: resin viscosity, cure behaviour, and thermal conductivity ; permeability of various fabric combinations using different techniques ; fabric preforming; edge and pore microstructure analysis; and correlation of mechanical properties with processing.

2 Software Development - data generated predominantly within tasks 1 and 3 was used to aid the development and partial validation of software to simulate the RTM process.

3 Validation - A number of laminates and typical structures of increasing complexity were manufactured utilising a range of processing parameters primarily to validate, troubleshoot and provide data for the software developments in tasks 2 and 4. This included some mechanical and component testing.

4 Intelligent Knowledge Based System (IKBS) Development - Using data generated from within the programme, a software based IKBS for RTM was developed and partially evaluated. Additionally work was conducted on mould and cure optimisation, void formation and finite element analysis.

The research was conducted by the pan-European consortium between November 1st 1992 and May 3^{1st} 1996. The work conducted has helped to advance the state of knowledge considerably in many areas including: resin characterisation; permeability of fabrics; preforming; mechanical property-processing correlation; optimum material selection and processing parameters; and software developments for simulations and IKBS. It has also highlighted where further work is required to resolve outstanding issues

INTRODUCTION

Resin transfer moulding (RTM) is a composite manufacturing process which dates back at least to the late 1940s (Bloodhound missile nosecones) and has in recent years gained increasing favour as a process which offers high tolerance components and the potential of reduced costs, reduced scrap and reduced operator exposure to harmful agents. Whilst RTM has been used for nearly fifty years, the technology to produce consistent parts without several trial runs and modifications has been restricted mainly to a few large companies and hence the process has been largely restricted to long runs and/or large companies. Consequently, information within the public domain with respect to the RTM process and simulation has until relatively recently has been sparse.

The aim of BRITE-EURAM project BE5477-92 which was started in November 1992 was to

to improve the design methods, process knowledge, simulation tools and general data available to enable the whole RTM process to be utilised with minimal iteration. This was performed in four mutually interactive tasks which can be broadly classified as:-

Task 1: Material Characterisation

Task 2: Simulation Software Development

Task 3: Validation

Task 4: Intelligent Knowledge Based System (IKBS) Development

By using the knowledge gained and software developed within this project, the ultimate goal of the project was to significantly reduce the development and manufacturing risks associated with the production of potential RTM components. By decreasing the risks of RTM manufacture, it is believed that many more companies, especially small and medium sized enterprises (SMEs), would benefit from the potential cost, performance, high tolerance, low waste and reduced operator exposure to harmful agents associated with RTM manufacture.

TECHNICAL DESCRIPTION

The approach taken by the consortium was to sub-divide the four main tasks into several smaller subtasks which involved one or more of the partners mentioned. Some activities were duplicated at different establishments in order to obtain a multiple approach to particular issues, for example, the measurement of fabric permeabilities which were performed initially at the University of Plymouth and TNO P&RRI and subsequently at the Swedish Institute of Composites (SICOMP) as it became apparent that permeability measurements were not quite as straightforward as envisaged.

Task 1: Material Characterisation

Isothermal viscosity-time curves for LY556, LY564-1 and RTM 6 epoxy and Arotran D6530 polyester resin systems were determined at various temperatures from ambient upto a maximum of 160°C using a Carrimed controlled stress rheometer at the University of Plymouth. Dynamic viscosity measurements using a steady state shear rate were also conducted and Non-injection point data were presented. Attempts were also made to utilise differential scanning calorimetry (DSC) under equivalent conditions to provide data for phenomenological models but was discarded as instrument baseline drift was found to be too high at low temperatures and reaction too rapid at elevated temperatures.

Fabric permeability measurements were conducted at the University of Plymouth and at TNO P&RRI and subsequently a limited number of correlation checks were performed at SICOMP. The Plymouth experiments utilised a radial flow technique and in essence consisted of an aluminium base plate with a glass cover and video camera to monitor the flow front. The TNO permeater consisted in essence of aluminium and glass plates forming the bulk of the mould cavity whose separation could be altered by screws in order to vary fibre volume fractions. The fluid is introduced under pressure at one end of the permeater, its pressure is monitored at five points along the length of the cavity prior to exiting at the other end of the permeater and the resin throughput is weighed. Plymouth utilised real resins and measured the permeability in a wetting state, whereas TNO used a glycerol-water mixture as a model fluid and measured the permeability

of a wetted fabric. A variety of glass and carbon fabrics of different lay-ups, tow sizes, volume fractions and degrees of shear, including a fabric from Brochier SA specifically designed to aid resin flow.

The cure behaviour of the resins mentioned previously were characterised by SICOMP and the University of Plymouth using DSC with the data being used to input into kinetic models. Limited resin thermal conductivity measurements were also made using modulating DSC and attempts were made to use Lee's disc apparatus. A brief assessment of dielectric spectroscopy of curing epoxies was also conducted by the University of Rigs using resins supplied by Brochier SA. Investigations into the characterisation of shaped fabrics were also performed by INASMET and TNO P&RRI utilising a range of glass and carbon fabrics. This included moulds, preforming techniques and handling trials. The University of Plymouth additionally performed work on edge effects and pore space microstructure analysis, the latter using image analysis techniques. Work conducted by Brochier SA and the Kungliga Tekniska Högskolan looked at how composite mechanical and physico-chemical values including short beam interlaminar shear strength, glass transition temperature, tension strength, compressive strength, flexural strength, and fracture toughness were influenced by processing parameters.

Task 2: Simulation Software Development

Data generated in the other tasks was used, to aid the development of software to simulate the RTM process and thus predict flow paths, dry spots, optimum gating, fill-times and heat transfer during cure. This task was planned to progress in levels of increasing complexity from simple two-dimensional isothermal simulation models to three-dimensional non-isothermal models. The simulation work started using the mainframe-based VIP/SEPRAN software, but due to numerous problems the software development was changed to a PC-based system and the Pi 7 software development initiated by TNO P&RRI, with the University of Plymouth also being directly involved in this activity.

Task 3: Validation

A number of laminates and component type structures of increasing complexity were manufactured using a variety of processing parameters in order to validate, trouble-shoot and provide general input to the other tasks. The University of Plymouth conducted two-dimensional moulding work and assessed the effects of flow front convergence join lines using short beam interlaminar shear strength results. INASMET and Brochier SA conducted investigations on both two- and three-dimensional simple mouldings. The level of complication was raised further to an intermediate level of complexity by Short Brothers who made both 'T' and 'I' beams and by SONACA SA who manufactured a skin panel with a cut-out and stiffeners. The most complex three-dimensional moulding was made by British Aerospace Airbus Limited who manufactured a complex aircraft spoiler panel comprising pre-formed foam cores and a number of carbon fabric preforms,

Task 4: Intelligent Knowledge Based System (IKBS) Development

Starting with a system specification, data and know-how generated from the rest of the programme was used by INASCO Hellas and INTRACOM SA to develop an IKBS with associated documentation to cover material selection, processing and mould considerations associated with the RTM process. The system was initially developed by INTRACOM SA using a

mainframe-based G2 software platform with assistance from INASCO Hellas. The knowledge gained was subsequently adapted by INASCO Hellas to utilise the PC-based KAPPA-PC expert system platform with assistance from INTRACOMSA.

SONACA SA also compiled a mould tool optimisation handbook with data inputted from a combination of literature searches, general partner comments and answers to specific questions. Within this task, work was conducted by SICOMP covering finite elemental analysis, a simple cure model for process optimisation and void formation in RTM.

RESULTS

The level of results presented in this document represents only a small fraction of the data generated within this project and has been summarised for reasons of space and to prevent the publication of sensitive data.

Task 1: Material Characterisation

The viscosity data showed dramatic differences in resin viscosity and reactivity between the viscosities of the resins characterised which would have a direct influence on the useable processing window of each system. The initial viscosities in mPa.s within the temperature ranges studied for the epoxy systems were as follows:-

L Y 5 5 6	-600 (25°C)	-30 (80°C)
LY564-1	-650 (25°C)	-70 (80°C)
R T M 6	-400 (80°C)	-25 :160°C)

Thermal characterisation of the same resin systems using DSC gave the following enthalpy of reaction and activation energy values, in units of joules per gramme and joules per mole respectively.

	Enthalpy	Activation Energy
LY556	294	82
LY564	438	58
RTM6	429	62

A large number of permeability values were produced by the three establishments performing the tests and used to input data into the simulation and IKBS tasks. The results of a particular material configuration were generally consistent for a particular technique/establishment, but there was poor agreement between the results generated by the different establishments for nominally the same material and configuration. This finding led to a list of factors which need to be considered when measuring fabric permeabilities being drafted as a reference and general aid, a copy of which is shown in Table 1. Graphical presentation of permeability data from the University of Plymouth for carbon fabrics indicated groupings such that the major permeability of warp aligned fabrics increased in the order satin < twill < Injectex (modified 5HS) and that the minor permeability of the same fabric types was in the order satin < Injectex < twill. The tow size of the fabric also influenced permeability due to the pore space architecture, with higher tow sizes exhibiting higher measured permeability values.

The results of the shaped fabric characterisation work indicated several factors including:

- pressure used has little effect on the preform quality
- preforms should be handled as little as possible
- due to the difference in binder chemistries, vacuum bag forming of carbon fabrics is preferred to press forming
- drawability of the 5HS carbon fabric was best and the unidirectional fabric the worst, but the drawability of the latter could be improved by cross-plying

Quantitative analysis of edge effects is very difficult due to the complicated fabric architecture. Analysis has also shown that the flow rate increases with the degree of fibre clustering (eg. large tows) and initial results suggest that compression and shear strength decrease as the flow rate increases. Within the limits of the work conducted, varying the processing parameters had an insignificant effect on the test values measured.

Task 2: Simulation Software Development

Both versions of software exhibited good agreement with the experimental results by predicting resin flow and dry spot areas. However, correlation with resin fill times was variable, especially for the more complex demonstrators, with both over- and under-estimations being made. At the conclusion of the project, work had still to be completed to develop a non-isothermal version and to make data transfer easier.

Task 3: Validation

This activity produced a vast amount of practical data and experience on 'how to' and 'how not to' produce good RTM components which was used to validate and input to the software packages. There were many factors found to be important in producing good RTM components including: pressure, especially at high volume fractions and low permeabilities; the relationship between resin temperature, resin reactivity and maximum process time; mould design and temperature; flow path length; flow join lines; mould design and temperature; the position of injection and exit ports; and component complexity. The most complex component demonstrator produced was the 'British Aerospace Airbus Ltd. spoiler, as shown in Figure 1. This measured 177 x 63 x 6cm, comprised an internal C-spar, foam cores, several preforms and proved the most difficult component to accurately simulate.

Task 4: Intelligent Knowledge Based System (IKBS) Development

Both mainframe and PC based IKBS software systems were developed and documented, but there was limited opportunity to fully evaluate them. An extensive document was also produced covering all possible mould tool optimisation considerations including: economic aspects; tool design; material selection; clamping and heating; and miscellaneous points such as seals, surface roughness and tool preparation. Investigation of void formation and dissolution in RTM processing showed that the rate of dissolution is dependent on the gas and resin, with the rate being higher in polyesters than in epoxies of those resin types studied. The ease of void transport is also dependent on capillary effects, pressure and viscous effects. Ultrasonic NDE and subsequent destructive examination showed an approximately linear relationship between void content and attenuation with only a slight influence from changing fibre volume fraction.

CONCLUSIONS

Significant advances have been made in the understanding of most aspects of the RTM process ranging from the initial selection of fibre and resin to simulation and the production of complex components by RTM. This information is now available to a range of establishments across Europe to act as a basis for further research (not necessarily in RTM), to be used for consultancy purposes and to be commercially utilised in making RTM components or selling software when fully developed.

The majority of the initial aims and objectives of the project were achieved, but as with any research projects, some issues were found to be more complex than initially perceived and could not be fully resolved or developed within the programme. This is true of both the permeability measurements and the simulation software, but for which significant advances in the state of the art were made.

It is possible to state that the apparent fabric permeability measured is a function of how the measurement is made and that there are many factors to be considered when choosing the technique to be employed (ref. Table 1). However, it is not possible to state which technique, if any, gives the 'correct' answer under all conceivable circumstances where permeability data are required and hence further work would be required to fully resolve the measurement of this fundamental parameter.

The approach adopted of having several mutually interactive tasks subdivided into several smaller subtasks was a successful way of managing this large project. The use of incremental changes in levels of complexity and validation was also found to be successful in developing the simulation software. However, in developing an IKBS it was found that the most appropriate approach to use was to start with the most complex model and decrement the levels of complexity as required to match the component being modelled.

The knowledge and databases generated within this programme on all aspects of RTM technology have reduced the risks associated with the development of any potential RTM component by increasing the chances of making a component right first time. Provided a good quality injection has been achieved, the mechanical and physico-chemical properties of the resultant component has been found to be little affected by the processing parameters used and thus the RTM process may be regarded as being robust.

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Table 1

Potential Problems in the Measurement of Reinforcement Fabric Permeabilities

Parallel Flow

- Edge effects and easy paths can dominate flow
- Separate expts. are required for each direction
- Direct use of Darcy's equation
- Data is integrated over fluid collection period

Wetted Flow

- May not adequately represent the flow situation in RTM
- No flow front can be discerned
- Capillary effects are not present
- Leakage paths from intratow to intertow flow are not present
- Mass and volume flow should be equal

Variable Cavity

- Variable mould height may be subject to-relaxation

Model Fluids

- Molecules smaller than resin may flow through finer pores
- Viscosity of glycerol is a strong function of water content
- Contact angle may be wrong for RTM simulation
- Information is lost at the end of the experiment for non-curing fluids
- Significant differences in permeabilities have been reported with different fluids

Constant Flow Rate

- Visual record of flow front is not essential
- Rigid tool minimises cavity distortion
- Sampling limited to the number of transducers available

Radial Flow

- Surface effects and easy paths may dominate, especially if high injection pressures force fabric away from injection port
- Single experiment yields full 2-D tensor and transformation matrix
- Observation of $+0^\circ$ effectively permits crosscheck within the experiment
- Complex algorithm to compensate for geometry
- Individual isochrones are required: data is fitted to the progression of these lines. A windowing algorithm may be used to confirm consistency of the permeability value.
- A hole in the fabric may be required to ensure plug flow, but is not implicit in the theory
- with no hole, the pressure drop through the fabric may be significant
- calculated permeability may be sensitive to measured hole size

Wetting Flow

- Similar flow situation to RTM
- Difficult to discern actual position of leading flow front and full wetting in intertow gaps
- Fingering in unidirectional fabrics can be significant, the latter are assumed to be small
- Leakage paths from intratow to intertow flow are present
- Mass flow and apparent volume flow may differ (possibly giving information about the above leakage flows)

Fixed Cavity

- Clamping to ground flat stock may still permit relaxation of fibre fibres

Resin

- Use of resin simulates actual RTM process
- Viscosity is a function of temperature and cure
- Contact angle is accurately represented
- Cured plate can be measured to confirm cavity size and individual fibre positions, but may not completely represent the dimensions during flow

Constant Pressure

- Requires visual record of flow front position
- Transparent materials are predominantly less rigid
- Full flow front isochrone recorded

General Comments

- Low viscosity may cause experimental problems
- Determination of fibre volume fraction is experimentally difficult during flow

Mould Flexibility

- Vacuum may cause inward deflection \rightarrow high $V_f \rightarrow$ low permeability
- Pressure may cause outward deflection \rightarrow low $V_f \rightarrow$ high measured permeability

FIGURE 1

British Aerospace Airbus Limited Demonstrator Panel ,

