SWEDISH DEFENCE
RESEARCH AGENCY

FOI-R--1035--SE
December 2003
ISSN 1650-1942

Base data report

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Microwave curing polymer composites

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Issuing organization FOI – Swedish Defence Research Agency Sensor Technology P.O. Box 1165 SE-581 11 Linköping	**Report number, ISRN** FOI-R--1035--SE	**Report type** Base data report
	Research area code 7. Vehicles	
	Month year December 2003	**Project no.** E3037
	Customers code 5. Commissioned Research	
	Sub area code 74 Materials Technology	
Author/s (editor/s) S.J. Savage	**Project manager**	
	Approved by	
	Sponsoring agency	
	Scientifically and technically responsible	
Report title Microwave curing polymer composites		
Abstract (not more than 200 words) This report briefly reviews the status of microwave hardening polymer composites. A survey of relevant activities in Sweden has been made, and it appears these are very limited. Some activity in the UK has been identified. Details of the contacts made during preparation of the report are given, and an annotated bibliography of relevant publications is included. Microwave hardening of polymer composites is compared with industrial techniques for sintering (metal and ceramic powders) and timber drying.		
Keywords microwave hardening, polymer composites		
Further bibliographic information	**Language** English	
ISSN 1650-1942	**Pages** 16 p.	
	Price acc. to pricelist	

Utgivare Totalförsvarets Forskningsinstitut - FOI Sensorteknik Box 1165 581 11 Linköping	**Rapportnummer, ISRN** FOI-R--1035--SE	**Klassificering** Underlagsrapport
	Forskningsområde 7. Farkoster	
	Månad, år December 2003	**Projektnummer** E3037
	Verksamhetsgren 5. Uppdragsfinansierad verksamhet	
	Delområde 74 Materialteknik	
Författare/redaktör S.J. Savage	**Projektledare**	
	Godkänd av	
	Uppdragsgivare/kundbeteckning	
	Tekniskt och/eller vetenskapligt ansvarig	
Rapportens titel (i översättning) Mikrovågshärdning av polymerkompositer		
Sammanfattning (högst 200 ord) Denna rapport innehåller en lägesbeskrivning av mikrovågshärdning polymerkompositer. Relevanta aktiviteter och aktörer i Sverige sammanfattas, de är dock mycket begränsade. Aktiviteter i Storbritannien har identifierats. De relevanta kontakter som gjorts under arbetet har inkluderats, och litteraturen har kommenterats. Mikrovågshärdning av polymerkompositer jämför med industriella tekniker för sintring av keram- och metallpulver, samt torkning av trävirke.		
Nyckelord mikrovågshärdning, polymerkompositer		
Övriga bibliografiska uppgifter	**Språk** Engelska	
ISSN 1650-1942	**Antal sidor:** 16 s.	
Distribution enligt missiv	**Pris: Enligt prislista**	

CONTENTS

Introduction

Dual use (military-civilian) of materials technology is growing rapidly, due to the increasing demand from civilian markets for highly advanced materials in the information sector, manufacturing industry, aerospace, automotive and medical technology sectors. In many instances, it is the civilian market which is today providing the main driving force for materials development, in contrast to the period from around 1950 to 1985, where in many cases defence requirements provided the main driving force.

The use of microwave curing of thermoset resins has been identified as a technology where existing knowledge may be applied to an area which is growing in both civilian and military importance.

Motivation

There are many common features between the application of microwaves to cure thermosetting resins (”epoxy”) and the use of microwaves (radar) to (a) detect and identify military targets and (b) avoid detection by radar. The major significant difference is of course the power dissipated in the material. Radar signals are very low power density when received at the target, whereas microwave radiation used to heat a resin may be of the order of 100’s of W/m^2 or even kW/m^2.

In both cases a detailed knowledge of the interaction of microwave radiation with materials is important.

There is a growing interest in using fibre reinforced composites for structural purposes in both civilian and military applications. Glass fibre and carbon fibre composites have proven to be practical, cost effective and weight effective materials in applications ranging from shipbuilding, bridges and aeroplanes to ballistic protection and the hulls of armoured personnel carriers. The latter application is of particular interest in lightweight military vehicles, and is being studied in the USA, Great Britain and Sweden. A particular advantage is the potential to combine the mechanical requirements for a lightweight, strong and stiff vehicle hull with the requirements to provide integrated ballistic protection in the structure. Glass fibre reinforced polymers have been shown to be promising in this application.

Common to all these applications is that thicker composite sections are being constructed. For the armoured personnel carrier and similar applications, section thicknesses of 100 mm and greater are required. Using conventional (autoclave) heating to cure the composite leads to large thermal gradients due to the poor thermal conductivity of both the reinforcing glass fibre and the polymer matrix. Autoclave heating, where thermal energy is transferred into the material by conduction and radiation occurs via the surface, whereas microwave heating occurs via direct molecular interaction throughout the material, thereby reducing thermal gradients.

Reducing the thermal gradients during curing is expected to lead to the following effects:

- Reduced curing times
- Reduced residual stresses after completed curing
- Improved energy efficiency
- Improved homogeneity of curing

Activities

An inventory of the present state of knowledge, and interest in the possibility of using microwave curing to produce fibre reinforced composites has been made, primarily within Sweden, but also in the UK and Europe. Results of this inventory, with the names and other details of the persons contacted are given below.

IFP-SICOMP

The Institute for fibre and polymer technology, with locations in Borås; Mölndal; Kristianstad; Västervik and Piteå (tel: 031 706 6300; fax: 031 706 6363) combined with SICOMP: *the Swedish Institutes of Composites* during 2000 (tel: 0911 744 00; fax: 0911 744 99). They are now known as IFP-SICOMP (http://www.sicomp.se). Address: IFP-SICOMP; Box 271; 941 26 Piteå.

Contact persons: Lars Liljenfeldt (tel: 0911 744 00), marketing manager recommended contacting Joakim Pettersson (tel: 0911 744 09), process expert, who recommended contacting Mikael Skrifvars (tel: 0911 744 15).

Neither institute has any current activities or experience (nor have they had in the past) in microwave curing, although interest was expressed in being informed of any developments in the area. SICOMP is the institute most suitable as a potential collaborator.

Skrifvars thinks microwave curing is clearly an interesting area. Using chemical hardening (organic peroxides) the polymerisation reaction begins within 30-60 minutes, limiting the time available to fabricate the composite. Microwave curing would allow more time, and selective hardening. The temperatures involved are not excessive, about 100 °C. A portable (transportable by truck) microwave curing unit would be useful, for field use, e.g. bridge repairs. There are no experimental facilities for microwave curing available.

FOI

1. The division of aeronautics (FFA) in Bromma had a department of Structures and Materials (now incorporated into department of computational physics), primarily interested in carbon fibre reinforced composites for aerospace structures.

Contact persons: department head Anders Blom (tel: 08 5550 4260) and research leader Sören Nilsson (extension 4369).

Structures studied at FFA are generally relatively thin (up to about 15 mm), and therefore autoclave curing does not lead to excessive thermal gradients. However, reduced process times, and elimination of the heavy capital and equipment investments required for autoclave curing would be an advantage. Interest was expressed in being informed of any further developments in the area. There is no current activity or experience of microwave curing at FFA, although both contacts thought the idea has some merit and requested to be kept informed of any developments. There are no experimental facilities for microwave curing available.

2. The division of weapons and protection at Grindsjön has a department of Materials and Protection, primarily interested in materials for ballistic protection, and the properties of such materials during rapid deformation.

Contact persons: Fritz Larsson (now retired, home tel: 08 819300) and Martin Nilsson (extension 3470).

There is little current activity in composite materials, although this was previously an area of research. Neither of these have any experience (current or prior) of microwave curing. There are no experimental facilities for microwave curing available.

3. The division of sensor technology has a department of Microwave Technology, primarily studying microwave circuits, antennas (group- and wide-band) and protection against high power microwaves.

Contact person: Ulf Dahlgren (extension 8414), and Niklas Wellander (extension 8438).

This department has no current or prior experience of microwave curing, although they thought the idea had some merit. There may be some possibility to apply existing knowledge of antenna design for design of equipment for microwave curing. Wellander has experience of homogenising theory, which could be used to model the interaction between microwave radiation and non-homogeneous material, e.g. fibre composites.

FMV

The competence centre for protection (KC Skydd) at FMV has an interest in fibre composites both as ballistic protection and as a construction material for armoured personnel carriers.

Contact persons: specialist Anders Nilsson (tel: 08 782 5584) and Patrik Persson (tel: 08 782 4231).

FMV has no experience of microwave curing, but considers the idea interesting. Manufacture of thick section (about 100 mm) glass fibre composites is an important and interesting area. FMV has cooperation with both the USA and UK in this area, especially the UK. A problem is the limited time available for injection of the resin during resin transfer moulding of thick composites when chemical polymerization is used. Microwave curing would extend the time available, and thereby possibly reduce the number of defects. FMV has no information on any companies or other organisations in Sweden or elswhere working with microwave curing, but recommended contacting Qinetiq, Ltd in the UK. FMV wished to be kept informed of any developments.

KTH

The department of Fibre & Polymer Technology is a logical site to contact for information on polymer and composite manufacturing technology.

Contact persons: prof Ulf Gedde (tel 08 790 7640) and prof Anders Hult (tel: 08 790 8268), address KTH, 100 44 Stockholm.

Neither Gedde nor Hult have experience of microwave curing, however, Hult has recently supervised a project on the use of electron beam curing resins for composites. Some of what was learnt during this project may be relevant for microwave curing, and electron beam curing also has the advantage of acting through the thickness of a structure. This work was reported as a poster contribution at a conference in 1999[1]. They confirmed the advantages of reducing thermal gradients during curing. There are no experimental facilities for microwave curing available.

Europe

The European Union has a number of Joint Research Centres (JRC's), some of which have activities in the area of fibre reinforced polymers. Two centres were contacted.

The Netherlands

The Institute for Advanced Materials-IAM, address: P.O. Box 2, 1755 ZG Petten, The Netherlands
Contact person: marketing director Dr. Carlo R. Chemaly (tel: +31 224 56 51 59, e-mail: chemaly@jrc.nl)
No one at IAM is working on this aspect of polymer processing, and IAM had no information about any European organisations working in the area.
Italy
The Institute for Systems, Informatics and safety-ISIS, address: ISIS – T.P. 361, I-21020 Ispra (VA), Italy.
Contact person: marketing director Dr. Jurgen Sanders (tel: +39 0332 78 9322/9511, e-mail jurgen.sanders@jrc.it)
There is no current activity in microwave curing at ISIS, or to his knowledge at any of the other JRC's, nor has this been an activity in the recent past.

United Kingdom

Via FMV a contact at Qinetiq (previously DERA) was obtained.

Contacted persons: project manager for composite armoured vehicles Dr Mark French, Qinetiq, Chertsey (tel: 01344 63 34 04, address: Chobham Lane, KT16 0EE, UK), referred contact to Dr. Marcus Simmons, Qinetiq, Farnborough (tel: 01252 39 72 80), referred contact to Dr. Aviva Howard, Farnborough, mechanical sciences centre (tel: 01959 51 56 18).

DERA (Qinetiq) recently (in 2000) completed a preliminary study into the use of microwave curing thermoset resins for fibre reinforced polymers. A report was being written, and this would probably not be secret. However, Dr. Howard would not release it without higher authority. From the little she was able to say it appeared that the initial tests made had been at least partly successful in meeting their goals, however, due to the privatisation of this part of DERA additional funding of the project was not expected in the near future.

Some contacts were made to investigate the possibility of obtaining the report referred to. A Defence Exchange Agreement (DEA) exists between Sweden and the UK which would cover this. A Mr. David Roberts at the Ministry of Defence (MoD) in the UK is the responsible officer (tel: 0171 218 11 12). He has not yet been contacted.

Microwave processing

Microwave processing has been used routinely for industrial production in a number of ways for many years. Applications include heating/drying timber, drying of food products and sintering of ceramic and metal powders.

Timber drying

Microwave drying timber leads to more homogeneous temperatures and drying, and a more controlled and rapid process, compared to traditional drying in warm air ovens. This results in a better quality product, and reduced manufacturing times and costs.

Ceramic powder sintering

Microwave sintering of ceramic products is a rapidly growing area. During sintering it is important to maintain a homogeneous temperature distribution, to prevent cracking and uneven shrinkage during the sintering process, and to minimise residual stresses after cooling. An even temperature distribution also leads to a more homogeneous microstructure. As some grain growth often occurs during sintering, an homogeneous temperature will lead to less variation in grain size (and therefore more homogeneous mechanical properties) in the finished product.

Conventional sintering uses radiative heating, which, due to the low thermal conductivity of ceramics (especially those not yet fully dense) leads to large temperature gradients and long process times. Processing times can be reduced considerably if heating can be achieved throughout the green body (pressed ceramic powder). Microwave heating has in a number of studies been shown to be successful, but there are some aspects which must be carefully addressed. The dielectric properties of ceramic materials vary considerably with temperature. In general, ceramics at low (room) temperature do not readily absorb microwave radiation at the most common industrial frequency of 2.45 GHz. As the temperature increases however microwave absorption increases, which can lead to thermal runaways. A hot spot can develop, where the temperature locally is slightly higher, which leads to increased (microwave) energy absorption, leading to a further temperature increase, and so on. Temperatures high enough to melt the ceramic locally have been observed.

To avoid thermal runaway and improve process control it is possible to use a combination of both radiative heating using traditional furnaces (but with reduced temperature and power requirements) and microwave heating. This reduces the difficulties in obtaining powder absorption in the ceramic body at low temperature, as initial heating is achieved by radiative heat transfer. As the temperature increases, continued heating is achieved by microwave power absorption.

Microwave sintering of ceramics is becoming established as a routine manufacturing technology. For a review of microwave processing of ceramics see [2]

Metal powder sintering

One might expect to obtain the same improvements with metal powder sintering as with ceramic powder sintering. However, there are some differences in the problems experienced, and it is clear that at present the technology for microwave assisted metal powder sintering is much less mature.

Metal powders, being excellent (compared to ceramics) electrical conductors, reflect most of the incoming microwave radiation, and therefore a heating effect is not obtained. However, there are some industrial projects aimed at overcoming this difficulty, including at least one international project based in Sweden. Details of this project are not given here, for confidentiality reasons.

For more details of metal powder sintering see Agrawal et al [3, 4]

Microwave curing composites

As can be deduced from the contacts with various persons detailed above, there seems to be no activity in this area in Sweden, although the idea seems to be generally interesting and can be expected to lead to improved properties in terms of product homogeneity and reduced process times. The latter has been proven for microwave processed ceramic powder products.

Only in the UK, at Qinetiq does there seem to be any knowledge and experience of microwave curing composites. This lead has not been explored fully, in part due to the ongoing privatisation of parts of DERA (now Qinetiq) but there does seem to be some possibility to follow this up further.

For more information regarding the microwave processing of polymer composites see the annotated references in appendix 1.

From the brief literature survey performed it can be seen that a number of authors have studied the use of microwave processing for composite polymer materials. Although the literature identified is not extensive, a number of conclusions may be drawn.

Microwave processing can lead to the following positive effects in terms of material processing:

- Reduced process times
- Reduced energy consumption
- Improved product homogeneity
- Improved matrix-fibre interfacial strength
- Improved mechanical properties

A negative effect observed in microwave processed composites was an increased level of voids. However, this did not result in degraded mechanical properties, as the negative effect of the voids was countered by improved matrix-fibre interfacial strength. If the process parameters were optimised to take into account the reduced process time it is likely that void content could be reduced to the level normally observed in composites.

Microwave processed glass-fibre reinforced epoxies or glass-fibre reinforced polyesters exhibit mechanical behaviour different from conventionally cured materials, measured by tensile tests. The higher rates of temperature increase achieved using microwave heating cause a competition between the matrix flow and the crosslinking reaction which can be estimated by porosity variations. Higher mechanical moduli are also obtained, because of both an effect on chemical kinetics and a more homogenous distribution of temperature in materials.
Nevertheless, to provide such specific mechanical behaviours in microwave processed composite materials, a careful control of the experimental pressure parameters is requested.

Recommendations for further work

Continued work in this area is reliant on additional funding. It may be possible to obtain funding from EU sources e.g. the STINT programme or similar. This will require participation of members from other EU countries. This possibility has been raised with DERA/Qinetiq, who indicated an interest in participating. Additional EU participants will be required. There are indications, which have not been investigated, that some research on microwave composite processing has been done in France. This possibility should be followed up, with a more detailed literature search.

If additional funding becomes available, some small scale experiments should be made, to confirm some of the literature results, and to gain practical experience of microwave processing composites, using existing equipment if possible. This study has not revealed any equipment which is directly suitable, but microwave ovens are commonly available, and could be modified without great difficulty so that some provisional experiments could be made.

References

1. T. Glauser, A. Hult, M. Johansson, *Electron-beam curing of resins for composites*, presented at EUROMAT conf., Munich, Germany, 1999.
2. D.K. Agrawal, *Microwave processing of ceramics.* Current Opinion in Solid State and Materials Science, **3**(5) (1998) 480-485.
3. D.K. Agrawal, *Metal parts from microwaves.* Materials World, **11** (1999) 672-3.
4. R. Roy, D.K. Agrawal, J. Cheng, S. Gedevanishvili, *Full sintering of powdered-metal bodies in a microwave field.* Nature, **399** (1999) 668-70.

Appendix 1 Annotated references on microwave curing polymer composites

D. Acierno, M. Frigione, V. Fiumara, D. Napoli, I.M. Pinto, M. Ricciardi. Materials Research and Innovation **2** (1998) 28-32. *Thermal and dielectric properties of thermal and microwave cured thermoset polymers*.
Abstract: We compare microwave and thermal curing of DGEBA thermosets hardened with BDMA catalyzed HHPA. The glass transition temperature and (complex) dielectric constant are monitored throughoout the process, for variable hardener contents and curing times.

D. Acierno, L. di Maio, M.E. Frigione. Conf. Proc. Microwave: Theory and Applications in Materials processing IV, American Chemical Society **80** (1997) 409-416. *Selected issues in the microwave processing of polymers*.
Abstract: This paper addresses a possible approach to three different topics in microwave polymer processing: measurement of dielectric properties, numerical modelling of microwave induced cross-linking, and microwave heating with melting fronts. Some new results, open issues and hints for future research are reviewed.

C. Akyel, E. Bilgen. Energy **14** (1989) 839-851. *Microwave and radio-frequency curing of polymers: energy requirements, costs and market peneration*.
Abstract: In this study, the microwave/radio frequency curing of polymers is reviewed, the characteristics of curable polymers are discussed and the energy requirements for microwave/radio frequency curing are calculated. Finally, using these findings, a market penetration study is carried out to determine the potential Canadian market for microwave/radio frequency curing of polymers.

S.L. Bai, V. Djafari. Composites **26** (1995) 645-651*. Interfacial properties of microwave cured composites*.
Abstract: A unidirectional continuous E-glass fibre/epoxy composite was cured using microwaves. The mechanical behaviour of the composite was studied by in situ transverse tensile and short-beam bending tests. The mechanisms of rupture were analysed. By comparing microwave cured composites (MCCs) with thermal cured composites (TCCs) it was found that more voids exist in MCCs than TCCs. This difference is considered to be due to the shorter time and lower pressure of microwave curing. It appears that the fibre-matrix interface of MCCs is stronger than that of TCCS according to the experimental results and observations. The thermal gradient across the fibre-matrix interface seems to play a role in its final quality.

F.Y.C. Boey, W.L. Lee. Journal of Materials Science Letters **9** (1990) 1172-1173. *Microwave radiation curing of a thermosetting composite*.
Abstract: No abstract available

M. Chen, J.W. Hellgeth, T.C. Ward, J.E. McGrath. Polymer Engineering and Science **35** (1995) 144-150*. Microwave processing of two-phase systems: composites and polymer blends*.
Abstract: The objective of the current paper was to extend the relationships between complex polymer blends and microwave absorptivity that were formulated in the first

three papers of this series (1-3). The microwave processing of composite and polymeric blends via a cylindrical resonance wave cavity and a standing wave applicator is described. These polymeric materials were irradiated in a low power (<100 W) electric field at 2.45 GHz. Graphite-epoxy laminates were processed in both standing and travelling wave applicators. Rapid heating and curing were achieved in both cases. An observation of significance was that, with proper tuning of the travelling wave device (the precursor of a portable repair tool), it proved to be highly effective in processing. Additionally, a compatible blend of poly(methylmethacrylate) and poly(vinylidene fluoride) was heated in an applicator and the rates of temperature rise were demonstrated to depend on morphology.

L.H.L. Chia, J. Jacob, F.Y.C. Boey. Journal of Materials Processing Technology **48** (1995) 445-449. *Radiation curing of poly-methyl-methacrylate using a variable power microwave source*.
Abstract: Microwave curing has recently been used as an alternative to thermal curing in some thermosetting resins. Advantage of the process includes better process control, faster curing times as well as the ability to operate the process as part of a continuous conveying system. This paper reports on the study performed on microwave curing of methyl-methacrylate monomers. The tacticity of the polymer was analysed in-situ by NMR spectroscopy and compared with results obtained using a thermal approach. The results indicate that the tacticity for both were similar. The degree of conversion was also determined using IR spectrocsopy and plotted with time for microwave curing, and the results compared with thermal curing.

R.J. Day, S.H.C. Yau, K.D. Hewson. Plastics, Rubber and Composites Processing and Applications **27** (1998) 213-219. *Effect of microwave post-curing on micromechanics of model Kevlar-epoxy composites*.
Abstract: Microwave processing of materials has the potential to deliver several major advantages over conventional thermal processing. One of these is a decrease in the time necessary for manufacture since the microwave energy is absorbed throughout the body of the material rather than relying on thermal conduction and convection. Another potential advantage is that the power is directed to the sample; this together with the decrease in processing time leads to lower energy being consumed. One question that must be addressed for polymer composites is whether microwave processed composites are as high quality as thermally processed ones. In the present work the interfacial properties of Kevlar fibre reinforced epoxy composites post-cured by both conventional and microwave heating have been examined. Raman spectroscopy was used to measure the fibre strain distributions along embedded fibres and from this information the interfacial shear stress dstribution was calculated. The results show that the interfacial shear strengths and critical lengths of the microwave post-cured composites are comparable with those for thermally post-cured ones. This is potentially of interest in the commercial manufacture of composites since the process could be considerably shortened by the use of microwave post-curing, leading to lower cycle times and costs wthout any deterioration in the interfacial properties of the composites.

M. Delmotte, J. Fitoussi, J. Toftegaard-Hansen, C. More, H. Jullien, D. Baptiste. Mat. Res. Soc. Symp. Proc. **430** (1996) 607-612. *Mechanical behavior of microwave processed polymer matrix composites: the effect of the temperature increase rate*.

Abstract: Microwave processed glass reinforced epoxies or glass reinforced polyesters exhibit mechanical behaviors different from conventionally cured materials, relatively to tensile tests. The faster increases of temperature due to microwaves cause a competition between the matrix flow and the crosslinking reaction which can be estimated by porosity variations. Higher mechanical moduli are also obtained, because of both an effect on chemical kinetics and a more homogenous distribution of temperature in materials. Nevertheless, to provide such specific mechanical behaviors in microwave processed composite materials, a best control of the experimental pressure parameters is requested.

R.J. Lauf, D.W. Bible, A.C. Johnson, C.A. Everleigh. Microwave Journal November 1993 pp 24-34. *2 to 18 GHz broadband microwave heating systems*.
Abstract: A wideband microwave heating system has been developed using a high-power travelling wave tube (TWT) amplifier and a highly overmoded applicator cavity. The useful bandwidth is an octave or more with a single TWT and can be expanded by adding another TWT to cover a second band. The controlled, broadband processing techniques possible with this system resut in uniformity of power distribution over areas not possible with more conventional, fixed-frequency microwave heating approaches. This paper reports on a simple theoretical model of the variable frequency microwave concept and summarized the experimental results obtained to date. Applications include heat treating and sintering, polymer curing and plasma processing.

O. Meyer, N. Belhadj-Tahar, A. Fourrier-Lamar. Mat. Res. Soc. Proc. **430** (1996) 587-593. *Control of microwave process for polymer curing by dielectric property measurements in a broad frequency range, 1 MHz –10 GHz*.
Abstract: Let us present a new automatic system which couples a high power circuit (2.45 GHz) for heating with a low power one, for broad frequency band measurements of dielectric permittivity (1 MHz-10 GHz). The sample under microwave curing consists of an epoxy resin + hardener complex (DGEBA + DDS). The broad band spectra shows the existence of a dielectric relaxation. This absorption is used as a marker to describe the evolution of the reaction in relation with time and temperature, in terms of conversion ratio, kinetic velocity and quality. The phenomenon of microwave activation and interactions between permanent molecular dipoles and electromagnetic waves form the subject of the study. We also try to establish the specificity of microwave curing from a microscopic point of view. This work emphasises new concepts which concern microwave chemistry.

F.L. Paulausakas, A.D. McMillan, C.D. Warren. Mat. Res. Soc. Proc. **430** (1996) 493-506. *Adhesive bonding via exposure to variable frequency microwave radiation*.
Abstract: Adhesive bonding through the application of variable frequency microwave (VFM) radiation has been evaluated as an alternative curing method for joining composite materials. The studies showed that the required cure time of a thermosetting epoxy adhesive is substantially reduced by the use of VFM when compared to conventional (thermal) curing methods. Variable frequency microwave processing appeared to yield a slight reduction in the required adhesive cure time when compared to processing by the application of single frequency microwave radiation. In contrast to the single frequency processiing, the variable frequency methodology does not readily produce localized overheating (burnt or brown spots) in the adhesive or the composite. This makes handling and location of the sample in the

microwave oven less critical for producing high quality bonds and allows for a more homogeneous distribution of the cure energy. Variable frequency microwave processing is a valuable alternative method for rapidly curing thermoset adhesives at low power input levels.

B. Soesatyo, A.S. Blicbau, E. Siores. International Journal of Adhesion and Adhesives **20** (2000) 489-495*. Effects of microwave curing carbon doped epoxy adhesive-polycarbonate joints*.
Abstract: This paper reports on the effect of adding two types of carbon black; Vulcan 66 and Sterling, to epoxy adhesive in lap joint of polycarbonate sheet to improve the microwave curing characteristics. The maximum bond shear strength after a 30 s cure time was compared with the two carbon black types at various dopant concentrations. The addition of the Vulcan 66 carbon black resulted in the higher bond strength when compared to a Sterling carbon black. Microscopical analysis of the fractured joint was carried out using SEM, and residual stress was investigated with a polariscope. Raman spectra revealed changes in material characteristics resulting from microwave processing.

E.T.Thostenson, T.-W. Chou. Composites A **30** (1999) 1055-1071*. Microwave processing: fundamentals and applications*.
Abstract: In microwave processing, energy is supplied by an electromagnetic field directly to the material. This results in rapid heating throughout the material thickness with reduced thermal gradients. Volumetric heating can also reduce processing times and save energy. The microwave field and dielectric response of a material govern its ability to heat with microwave energy. A knowledge of electromagnetic theory and dielectric response is essential to optimize the processing of materials through microwave heating. The fundamentals of electromagnetic theory, dielectric response and applications of microwave heating to materials processing, especially fibre composites, are reviewed in this article.

C.Y. Yue, H.C. Looi. Composites **26** (1995) 767-773*. Influence of thermal and microwave processing on the mechanical and interfacial properties of a glass/epoxy composite*.
Abstract: The influence of two curing methods, namely thermal and electromagnetic radiation (microwave) curing on the mechanical properties of a glass fibre/epoxy model composite has been studied. The advantage of microwave processing is that it leads to significantly faster curing times compared to thermal processing. The influence of the processing technique on the mechanical and interfacial properties was determined. The interfacial properties include the interfacial shear (bond) strength τ_i, the matrix shrinkage pressure on the fibre P_o, the interfacial coefficient of friction μ and the interfacial frictional shear stress τ_f. The interfacial properties were determined from analysis of experimental data from pull-out tests. Based on these results, the effect of thermal and microwave processing on the mechanical properties of the glass fibre/epoxy composite system was elucidated.