Productivity Improvement Through The Use of Industrial Microwave Technologies

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ABSTRACT

Microwave processing of materials is a relatively new technology advancement alternative that provides new approaches for enhancing material properties as well as economic advantages through energy savings and accelerated product development. This paper presents a state-of-the-art review of microwave technologies, processing methods and industrial applications. The characteristics of microwave interactions with materials are outlined together with the challenges that difficult to process materials present. To fully realise the potential benefits of microwave and hybrid processes, it is essential to scale-up process and system designs to large batch or continuous processes. This necessitates computational modelling and simulation, system design and integration and a critical assessment of the costs and benefit analysis. Impediments to industrial applications are identified and development opportunities that take advantage of unique performance characteristics of microwaves are discussed. Clearly, advantages in utilising microwave technologies for processing materials include penetrating radiation, controlled electric field distribution and selective and volumetric heating.

The aim of the work presented in this paper is to help guide those interested in using microwaves to improve current materials processing. Microwave fundamentals are described to provide a brief awareness of the advantages and limitations of microwaves in the processing of materials. Furthermore, the limitations in current understanding are included as a guide for potential users and for future research and development activities. Examples of successful applications are given to illustrate the characteristics of materials, equipment and processing methods applicable to industrial microwaves. Economic considerations are described and costs are provided as guidelines in determining the viability of using microwaves for processing materials.

1. INTRODUCTION

The word *microwave* is not new to every walk of life as there are more than 60 million microwave ovens in households all over the world [1]. On account of its great success in processing food, people believe that the microwave technology can also be wisely employed to process materials, eg cross-link polymers or sinter ceramics. Microwave processing of materials is a relatively new technology that provides new approaches to improve the physical properties of materials; alternatives for processing materials that are hard to process; a reduction in the environmental impact of materials processing; economic advantages through energy savings, space, and time; and an opportunity to produce new materials and microstructures that cannot be achieved by other methods. Microwave characteristics that are not available in conventional processing of materials consist of [1]: penetrating radiation; controllable electric field distribution; rapid heating; selective heating of materials and self-limiting reactions. Single or in combination, these characteristics lead to benefits and opportunities that are not available in conventional processing methods.

The above characteristics also present adverse effects in materials processing. First, due to inadequate penetration of the microwave energy, bulk materials with significant ionic or metallic conductivity cannot be efficiently processed. Second, on account of their limited absorption of the incident power, insulators with low dielectric loss are difficult to heat from room temperature to the required temperature. Lastly, materials with loss factors that vary significantly with temperature during processing will lead to hot spots and thermal runaway. The most likely candidates for future production-scale applications will take full advantage of the unique characteristics of microwaves. Polymer, ceramic and composite joining processes and catalytic processes are enabled by selective microwave heating. The savings envisaged include timesaving, higher yield, and environmental friendliness.

2. FUNDAMENTALS OF MICROWAVES

Microwaves are electromagnetic waves that propagate through empty space at the velocity of light. In such a wave the time varying magnetic field may be regarded as generating a time changing electric field, which in turn generates a magnetic field and the process repeats. The frequency ranges from 300 MHz to 300 GHz. Industrial microwaves are generated by a variety of devices such as magnetrons, power grid tubes, klystrons, kystrodes, cross-field amplifier, travelling wave tubes, and gyrotrons [1].

At the customary domestic microwave frequency of 2.45 GHz, the magnetrons are the workhorse. Material processing [1] falls into this category. Other frequency band reserved for industrial applications are 915 MHz, 5.8 GHz and 24.124 GHz. Magnetrons are the tubes used in conventional microwave ovens found almost in every kitchen with power of the order of a kilowatt. Industrial ovens with output to a megawatt are not uncommon. Huge sums of money have been spent in developing microwave processing systems for a wide range of product applications. In general, microwave processing systems consist of a microwave source, an applicator to deliver the power to the load, and systems to control the heating. Most applicators are multimode, where a lot of filed patterns are excited simultaneously.

3. MICROWAVE/MATTER INTERACTIONS

The material properties of greatest importance [2] in microwave processing of a dielectric are the complex relative permittivity $\varepsilon = \varepsilon' - j\varepsilon''$ and the loss tangent, $\tan \delta = \varepsilon''/\varepsilon'$. The real part of the permittivity, ε', sometimes called the dielectric constant, mostly determines how much of the incident energy is reflected at the air-sample interface, and how much enters the sample. The most important property in microwave processing is the loss tangent, $\tan \delta$ or dielectric loss, which predicts the ability of the material to convert the incoming energy into heat.

During microwave processing, microwave energy penetrates through the material. Some of the energy is absorbed by the material and converted to heat, which in turn raises the temperature of the material such that the interior parts of the material are hotter than its surface as the surface loses more heat to the surroundings. This characteristic has the potential to heat large sections of the material uniformly. The reverse thermal effect in microwave heating does provide some advantages. These include rapid heating of materials without overheating the surface; a reduction in surface degradation when drying wet materials because of lower surface temperature; removal of gases from porous materials without cracking; improvement in product quality and yield; synthesis of new materials and composites. On the other hand, the negative effect is the formation of hot spots and cracking. Microwaves can be transmitted through various media without much loss; the applicator can therefore be remote from the power source.

By using single mode applicators, it is possible to focus the microwave energy to precisely heating selected areas. This enables one to heat selected regions between two materials to promote welding and joining. The adverse effect to this can be more costly and complex equipment.

The dielectric loss of some materials often increases exponentially when a critical temperature is reached. This permits very rapid bulk heating, resulting in significant reduction in processing time. At the same time, hybrid heating or insulation can control the possible thermal runaway. This characteristic enables the processing of low loss ceramics, where both rapid heating and high processing temperature are required.

Selective heating is achieved by the differential coupling of materials. Selective heating of internal or surface phases, additives or constituents enables heating of microwave transparent materials. Processing of a large number of composites is therefore dependent on the widely differential heating of a least one of the constituents. Hybrid microwave heating is also an example where selective heating has been wisely employed. Selective heating stops after certain processes have been completed. Self-limiting absorption can also occur when two materials with different coupling characteristics, such as SiC and ZrO_2, are simultaneously exposed to microwave energy. At room temperature, SiC is a lossy material but ZrO_2 couples with microwave poorly. The situation remains true up to 500^oC. Above a certain critical temperature, the loss factor of ZrO_2 increases rapidly with increasing temperature, exceeds that of SiC and absorbs most of the microwave irradiation. This phenomenon is employed to hybrid-heat low loss material from room temperature [1].

4. COST AND BENEFIT ANALYSIS

In addition to considering the advantages brought about by microwave processing of materials, the cost in implementing the process is also vital to industry. The cost of capital equipment for microwave processing differs widely and depends on power rating, frequency, size, applicator design, manufacturer and market volume of the equipment. Microwave processing equipment is usually higher in cost than its conventional counterpart eg oven heating or drying and fusion bonding [1]. The cost of a complete system [1,3] is approximately 1600-8000 Australian dollars per kW. The generator and the applicator are about 50% of the total. The power transmission, instrumentation and external materials' handling are 1600-4800 Australian dollars each. The installation cost is 5-15% of system cost. The operating costs include cost of energy, maintenance, repair and replacement. The cost to replace a magnetron is 2-20 Australian cents per kW.hour. The cost of electricity is around 10-20 Australian cents per kW.hour. Routine maintenance cost will be 5-10% of system cost. The overall energy efficiency in industrial microwave processing is 50 –70% [1,4]. A Canadian source [3] estimated that the energy savings in drying and firing of ceramics using microwave energy is as much as 80% of its conventional rival. In alumina sintering, the energy savings can be as high as 90%. There have been a number of reports of savings in time and improvements in productivity obtained by microwave processing [1,3]. These are summarised in Table 4.1.

Table 4.1. Time-Savings/Productivity Improvements

Materials	Process	Time savings	Productivity Improvement
Whiteware	Slip Casting	66%	immediate mould recycling
Whiteware	Drying	24 h to 8 min	
Whiteware	Overall Process	70%	6.25 pieces to 27 pieces per worker per day
Boron Carbide	Sintering	>90%	
Structural Adhesive	Curing	66%	66% cost reduction
Varnish	Curing	<70%	

5. COMPUTER MODELLING AND SIMULATION

Computer modelling and simulation can provide valuable information involving various aspects of microwave processing. Numerical modelling has a significant impact on the research of microwave processing of materials because without a detailed understanding of the electromagnetic field structure together with the induced heat and mass transport phenomena, it is impossible to achieve an optiomal design of the heating system. The first step to achieve the goal is to develop a computer software package that can predict the electromagnetic phenomena that arise in arbitrarily shaped microwave applicators and loaded with arbitrarily shaped materials using microwave energy. The electric and magnetic fields for a closed microwave system are governed by Maxwell's equations.

In the past the finite element method (FEM) has been employed with success to solve Maxwell's equations in the frequency domain [5]. Many researchers extended this method to three-dimensional electromagnetic field problems. In 1992, Jia, et al [6] presented a three-dimensional finite element algorithm for studying microwave field and power distributions generated in a multimode cavity. Recently, the finite-element time-domain (FE-TD) method [7] was applied to the analysis of multimode applicators, with regular computational domains, using edge elements. The Finite-Difference Time-Domain method is considered by many researchers to be one of the most accurate and simple for implementing numerical methods when solving electromagnetic problems. Yee described the basis of the first FD-TD numerical method for solving Maxwell's curl equations [8]. In recent years, there has been an increasing interest in the numerical simulation of microwave heating problems via a direct solution of Maxwell's equations using the FD-TD method. For problems involving general non-rectangular domains, 'stair-case' orthogonal approximations have been used. During 1990, a three-dimensional modified finite volume technique for solving Maxwell's equation was presented by Madsen and Ziolkowski [9], where the concept of dual cells formed by joining the barycentres of adjacent primary cells was used.

6. SUCCESSFUL MICROWAVE APPLICATIONS

Some successful industrial applications are outlined below: ceramic/ceramic matrix composite sintering and powder processing, polymers and polymer-matrix composites processing, microwave plasma processing of materials, and minerals processing. The potential benefits of microwave processing over conventional processes for ceramic processing include reduced processing time, improved product uniformity and yields, improved microstructure, and the ability to synthesise new materials [3]. Vulcanisation of rubber is the first successful commercial application of microwave processing for polymers. The process brought about increased throughput, reduced operating costs, product uniformity, reduced scrap, improved automation and process control, continuous vulcanisation rather than conventional batch processes, improved cleanliness and environmental compatibility. There are significant differences between microwave excited plasma and the common parallel-plate RF (13.56 MHz) plasma. The degree of ionisation is also greater in microwave plasma. In the diamond film formation process, the benefits of microwave excited plasma include energy efficiency, stability and reproducibility of the plasma, and potential for larger production scale. In mineral processing, the use of microwave energy brings about substantial benefits in reducing energy consumption and environmental pollution. By employing the differential coupling of energy and the differences in thermal expansion, microwave processing of ores separates the valued component in the ore and the waste material surrounding it efficiently. Thuery [10] has detailed more successful applications of microwave energy in industry.

7. VARIABLE FREQUENCY MICROWAVE (VFM) PROCESSING

This is an advancement alternative for microwave processing. The technique is geared towards advanced materials processing and chemical synthesis. It offers rapid, uniform and selective heating over a large volume at a high energy coupling efficiency. This is accomplished using a preselected bandwidth sweeping around a central frequency employing frequency agile sources such as travelling wave tubes as the microwave power amplifier. Selective heating of complex samples and industrial scale-up are now viable [11,12]. Successful applications are in the areas of curing advanced polymeric encapsulants, rapid processing of flip-chip (FC) underfills, materials characterisation, and structural bonding of glass to plastic housing [12,13].

8. SUCCESSFUL APPLICATIONS OF VFM FACILITIES

During VFM processing, a given frequency of microwaves would only be launched for less than one millisecond; the technology has been successfully applied to process parts that include metal pieces such as printed circuit board (PCB) without causing any arcing or damaging to the sample [5]. Another successful application of VFM processing is in bonding automotive parts with adhesives as primer. The ultimate shear strength of panels of chopped glass fibre reinforced urethane processed by VFMF is equal to that processed by conventional oven but the time required for processing is halved [5]. When compared with the fixed (2.45 GHz) frequency microwave processing, the ultimate tensile shear strength of VFM processed panels is the same as its rival but the power input is halved. In microelectronic industries, VFMF is employed to cure the Flip-Chip (FC) underfills. An independent study [6] found that the microwave does not damage the electrical properties, delamination and wire bond integrity of the semiconducting devices. In addition, the coefficient of thermal expansion and the glass transition temperature of the adhesive are almost identical to those observed for samples cured in a conventional oven. The greatest benefit of curing FC underfills using VFMF is timesaving and reduction of stress on bonded parts [5,6]. The timesaving is up to 750%.

9. CONCLUSIONS

From the above discussions, it will be clear that there are a lot of factors that have to be considered before employing microwave irradiation for processing materials. Not all materials are suitable for microwave processing and one has to match the special characteristics of the process. Blind applications of microwave energy in material processing will usually lead to disappointment. On the other hand, wise application of the technology will have greater benefits than has been anticipated. In the joining of thermoplastic composites, with araldite as primer, using microwave irradiation, it was not surprising that the curing time was much shortened. However, it was not expected that the tensile shear strength of the joints would be higher than for ambient curing [14]. In general, the savings achieved through microwave processing will be other than energy as the saving in this respect would not be enormous. The benefits will be in timesaving, increased process yield, environmental compatibility, space savings and unique characteristics of the products. VFM processing offers greater rapid, uniform and selective heating over a large volume at a high energy coupling efficiency than its fixed frequency counterpart.

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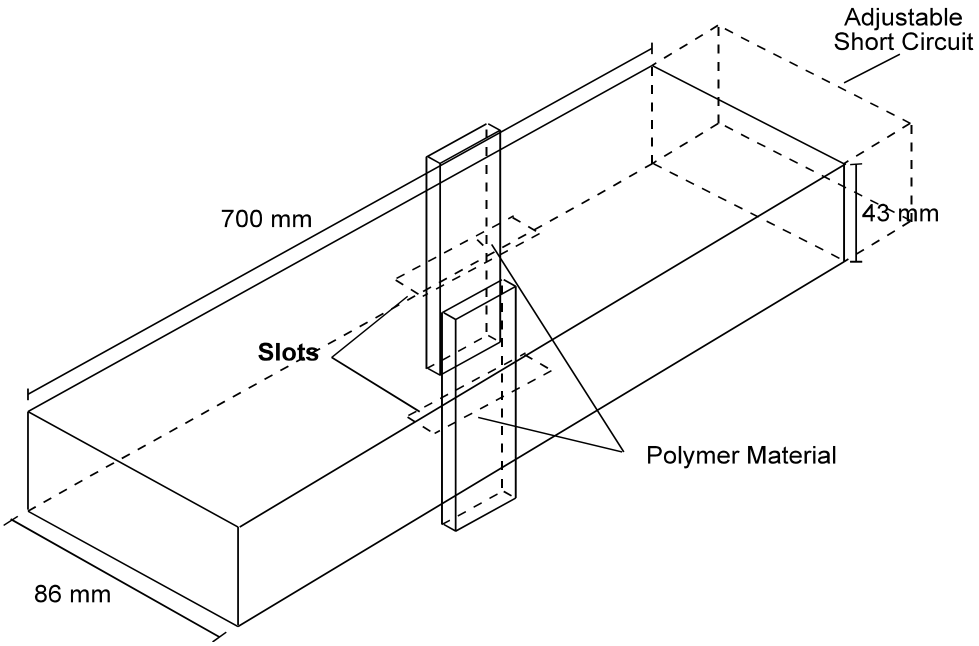

Figure 1: Numerical Simulation Result for Microwave Heating of Nylon 6 using the Power Input of 300W

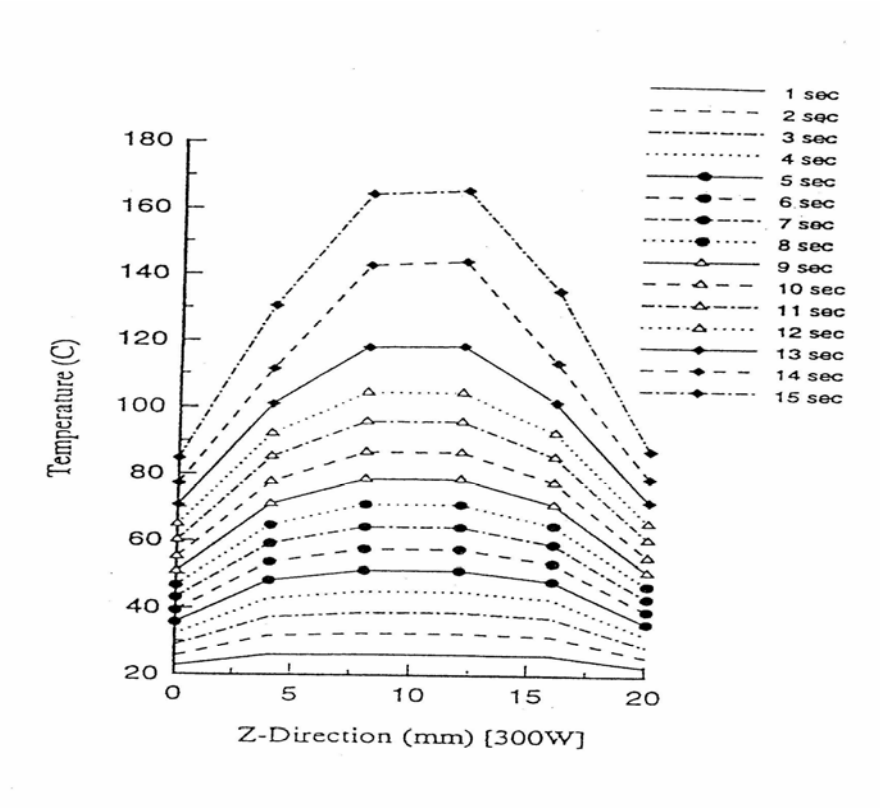

Figure 2: A Ridge Waveguide Results for Microwave Heating for a Polymer Material