Composite Material Processing in a Single Mode Cavity with Variable Frequency Microwaves

Yunchang Qiu and Martin C. Hawley

Department of Chemical Engineering
Michigan State University
East Lansing, MI 48824

SUMMARY: A computer controlled microwave processing system for polymers and composites is presented. The microwave circuit of the system comprises a variable frequency microwave power source and a single mode cavity. A computer data acquisition and control system has been developed to improve the heating uniformity and curing temperature stability by intelligently adjusting the frequency and power. Variable frequency mode switching technique was applied to achieve uniform heating. A parabolic power control algorithm was used to maintain the curing temperature so as to avoid thermal runaway. Heating results demonstrated the efficacy and stability of the control system. Flexural tests on samples heated for 90 minutes showed improved product quality resulted from decreased temperature gradients.

KEYWORDS: microwaves, variable frequency, single mode cavity, computer control, uniform heating, graphite/epoxy

INTRODUCTION

Over the decades, microwaves have been successfully applied in polymer and composite material processing, adhesive and repair, ceramic material processing, food processing, wood drying, waste treatment, and in medical use as well. Microwave technology was first used to process polymeric materials in late 1960s. However, there was only limited industrial application of this technology due to the non-uniformity of microwave applicators, lack of process control and poor understanding of the processes. Since the mid-1980s, there has been a resurgence of interest in the microwave processing of polymers and composites[1-6].

Microwave heating is instantaneous, volumetric and nonuniform in nature. Different modes have different electric field distributions, which are typically nonuniform. However, uniform heating has been obtained using combination of modes[7][8]. In a multi-mode oven, the applicator is over-moded and time averaged heating uniformity can be obtained by frequency sweeping[9]. Single-mode cavities can provide uniform heating using mode-switching method, in which several modes with complementary heating patterns are alternatively excited[10]. With a fixed frequency microwave power source, mode switching can only be achieved by mechanically adjusting the volume of the cavity. This mechanical process slows down the response of the system to temperature changes. When a variable frequency power source is available, the modes can be changed by varying the frequency. As a result of the instantaneous variable frequency mode switching, not only the speed of the process but also the controllability of the process is much improved.

With the implementation of computer control system for controlling the heating modes, the benefits of microwave heating can be fully utilized while achieving uniform processing. However, process control has not yet been widely practiced in microwave material processing. The first published automated single-mode resonant cavity was that developed by Alliouat et. al. [11] for sintering ceramic materials. The control system was based upon the elements of intelligent control for regulating the input power and for tuning the cavity. A gradient search method was used for tuning the cavity where the cavity length and reflected power were tuning parameters. Components of this processing include an infrared pyrometer for measuring the surface temperature, detectors for sensing the input, reflected and absorbed power. Controlled parameters were the microwave power level, and the cavity volume adjusted by stepper motors.

Adegbite et. al. developed an automated single-mode cavity in order to advance it as a viable process[7]. A control system was designed and built in addition to the development and implementation of a set of sophisticated and comprehensive control software programs for controlling the curing process in the cavity. These control programs combine traditional and non-traditional control methodologies. The control software programs were developed for mode tuning, mode selection and power control which were constructed independently and then integrated to form the overall closed-loop feedback control system. A mathematical 2-dimensional simplex method was used in constructing the tuning control software. Both coupling probe depth and cavity length were adjusted simultaneously to tune the cavity. A traditional PID (proportional-integral-derivative) methodology was used for the power controller.

To date, the implementation of control strategies is limited by the availability of good process models and by sensing technology in microwave processing. Most of the process models are either for a particular process and/or computationally very complicated. There are limited applications of the process models in the control of microwave processes. For microwave material processing, the important process variables are microwave power, electric field strength distribution, and the temperature, dielectric properties and cure state of the material. Except for microwave power and temperature, the sensing technology today can not provide accurate on-line measurement of these process conditions. Reliable sensing technology to detect the change of these process conditions during the processing can significantly advance material processing technology.

An automated microwave processing system with variable frequency power source and single mode cavity is presented in this paper. The control parameters were microwave frequency and power. Heating modes with certain frequencies were characterized before processing. The computer chose the frequency that can improve the temperature uniformity the most by comparing the heating characteristics at that frequency with current temperature distribution. When the maximum temperature reaches curing temperature, microwave power was adjusted so as to keep the maximum temperature at constant. Flexural tests were performed on the cured samples and comparisons were made in terms of heating uniformity. The performance of the control system is evaluated.

MICROWAVE CIRCUITRY

A diagram of the microwave circuitry with control system is shown in Figure 1. The power source is composed of an HP oscillator as signal generator and a Lambda VariWave power source as an amplifier. Microwave frequency can be adjusted from 2 GHz to 4 GHz through GPIB interface between the computer and the oscillator. Microwave power level can be modulated through a motor driven device that is controllable by the computer. The microwave applicator is a cylindrical single mode resonant cavity, the dimensions of which are 7 inches in diameter and adjustable from 4 inches to 10 inches in cavity length.

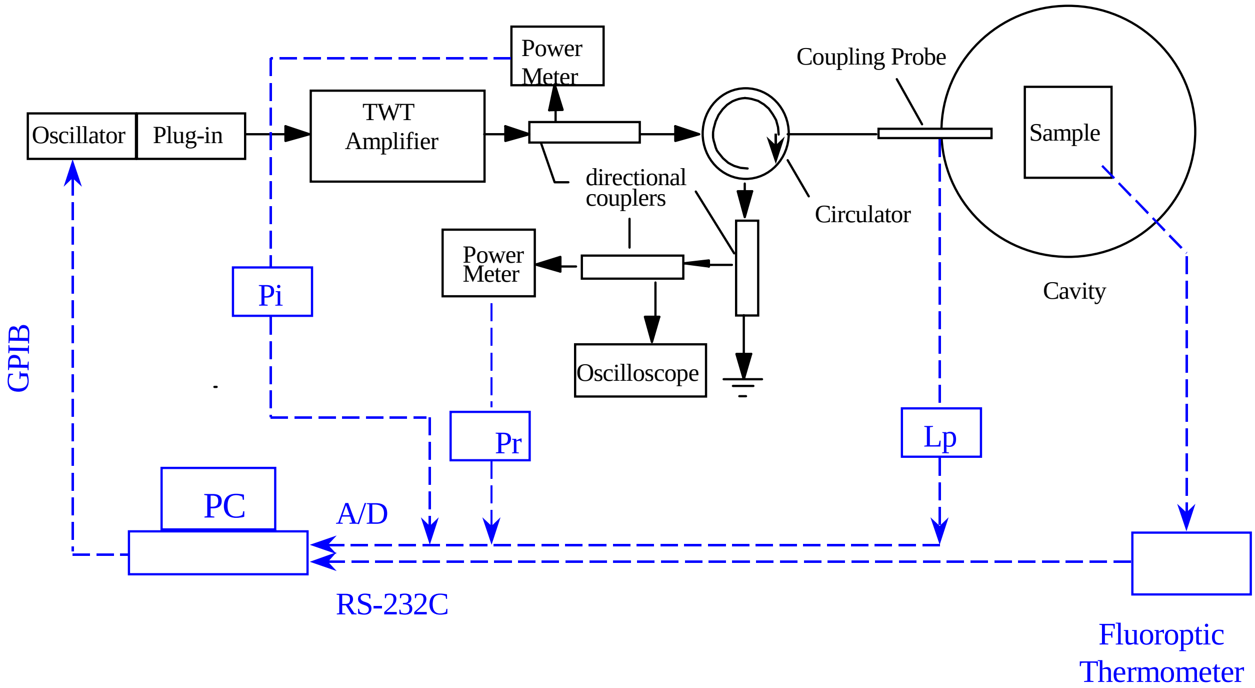

Figure 1. Automated Variable Frequency Microwave Processing System.

PROCESS CONTROL SYSTEM

The diagram of the process control system is presented in Figure 2. The software structure of the control system can be separated into two parts. One is aimed to maintain the curing temperature at a constant and the other is to improve temperature uniformity. At the curing stage, microwave power was modulated in order to keep the maximum temperature close to the curing temperature. During processing, the temperature distribution on the sample surface was monitored and the optimal frequency would be chosen to alleviate temperature gradients. The system was programmed in LabVIEW.

Mode Selection Program

A scan of reflected power versus frequency was carried out for the single mode cavity loaded with 3" by 3" square graphite/epoxy composite samples (Figure 5). Microwave fields were excited at the frequencies corresponding to the troughs and the heating profiles were obtained. The heating characteristics of each frequency (corresponding to a mode) are represented as the heating rates at the temperature measurement sites. At the beginning of processing, a frequency with most uniform heating profile was selected. When the temperature difference exceeds 10 degrees, using the heating rates the program will compute the expected temperature distribution when each mode is excited. Then the control system will switch the frequency to the mode with most uniform predicted temperatures.

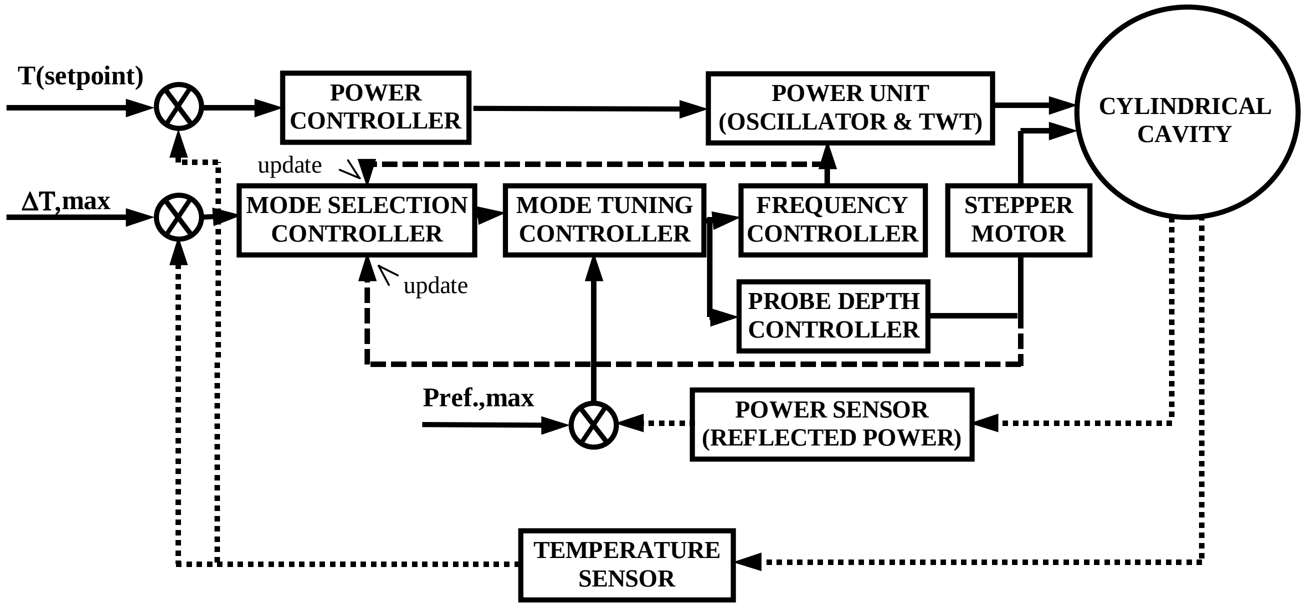

Figure 2. Block Diagram of the Control System.

Power Control Program

The purpose of the power control program is to maintain the maximum of the measured temperatures at the set point (the curing temperature of 160 ^oC). A parabolic algorithm was designed. If the maximum is higher than the curing temperature, then the microwave power will be turned off. If the maximum is 3 degrees lower than the curing temperature, then maximum power (100 watts) will be used. When the maximum of the temperatures is between 157 ^oC and 160 ^oC, the power output is parabolically related to the difference between the maximum temperature T and the curing temperature T:

$$P_i = (P_{\max} - P_{\min}) \times \left[\frac{T_{cure} - T}{T_{cure} - T_{low}} \right]^2 \quad (1)$$

Where Pi is the input power, P_{max} is the set maximum power (100 Watts), P_{min} is the set minimum temperature, T is the maximum of the measured temperatures, T_{low} is the lower end of the temperature control window (157 ^oC), and T_{cure} is the curing temperature. A curve representing the relationship is shown in Figure 3.

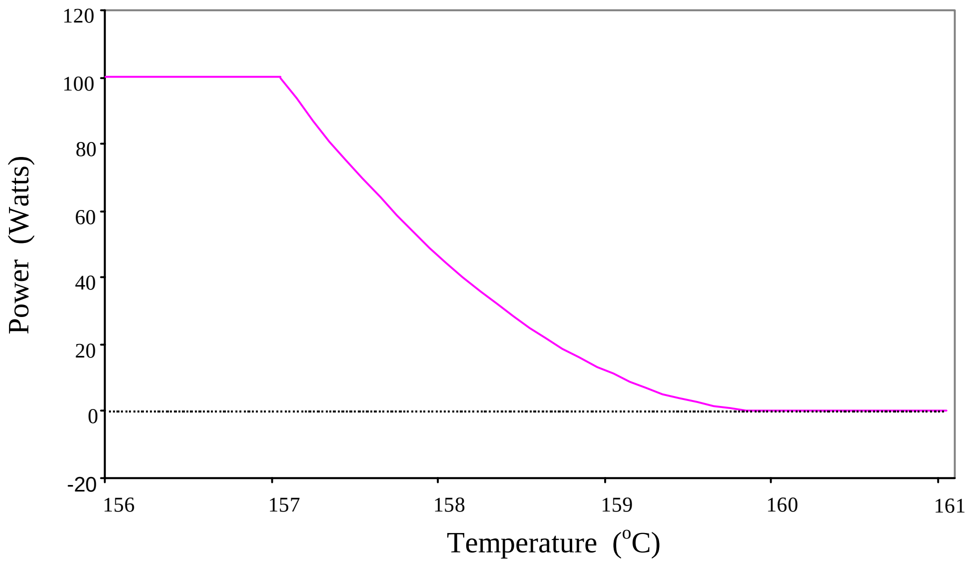

Figure 3. Power Temperature Relationship.

Control System Hardware

A sketch of the control system is presented in Figure 1. Microwave frequency is controlled by the computer through the GPIB interface with the HP oscillator. Microwave power is adjusted using the motor driven attenuator. Temperatures are measured using Luxtron fluoroptic probes.

RESULTS AND DISCUSSION

The material used in this study was Hexel AS4-3501/6 graphite/epoxy prepreg. 24-ply unidirectional 3" by 3" parts were processed. The samples were placed in a Teflon mold and eight temperatures were measured on the sample surface. The mold was placed on the bottom of the single mode cavity with cavity length of 15 cm and coupling probe depth of 20 mm. The configurations are shown in Figure 4.

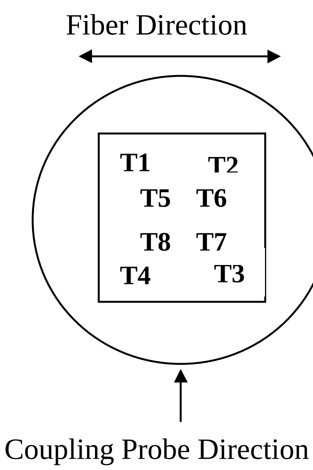

Figure 4. Temperature Measurement Locations.

Before the curing studies, a scan of percentage of reflected power versus frequency was obtained by sweeping the frequency from 2 to 4 GHz (Figure 5). The frequencies at troughs with low percentages of reflected power usually correspond to heating modes, which can heat the sample rather significantly. Single mode heating experiments were performed at these frequencies. The maximum of the measured temperatures was controlled at the curing temperature at curing stage. Most of the modes demonstrated large thermal gradients, usually more than 40 degrees when the maximum temperature is at 100 ^oC. As the heating went on at the curing stage, the thermal gradients were slightly reduced due to thermal conduction. There was one mode that showed rather uniform heating. The difference of the temperatures was within 20 ^oC at the curing stage. However, thermal gradients exceeded 30 ^oC during the heating up stage. The heating profiles of a typical nonuniform heating mode and the rare uniform heating mode are presented in Figures 6 and 7, respectively.

Six heating modes were selected for the mode switching heating experiment. The criteria of selection were the complimentariness of the temperature profiles and the heating efficiency. The frequencies of the modes are given in Table 1. The temperature profiles of the variable frequency mode switching heating are presented in Figure 8. As can be seen, thermal gradients were significantly reduced compared with single mode heating. The temperatures were controlled to be within a window of 15 degrees throughout the processing. However, the temperature profiles were less stable due to the combination of mode switching and power control. The change of modes selected during the processing is illustrated in Figure 9. The six modes were quite evenly used during the processing except for mode 5. The power adjustment is illustrated in Figure 10 .

TABLE 1. Frequencies of the Modes Used in the Mode Switching Heating

Modes	0	1	2	3	4	5
Frequency (GHz)	2.5772	2.7065	3.1009	3.1643	3.4415	3.6409

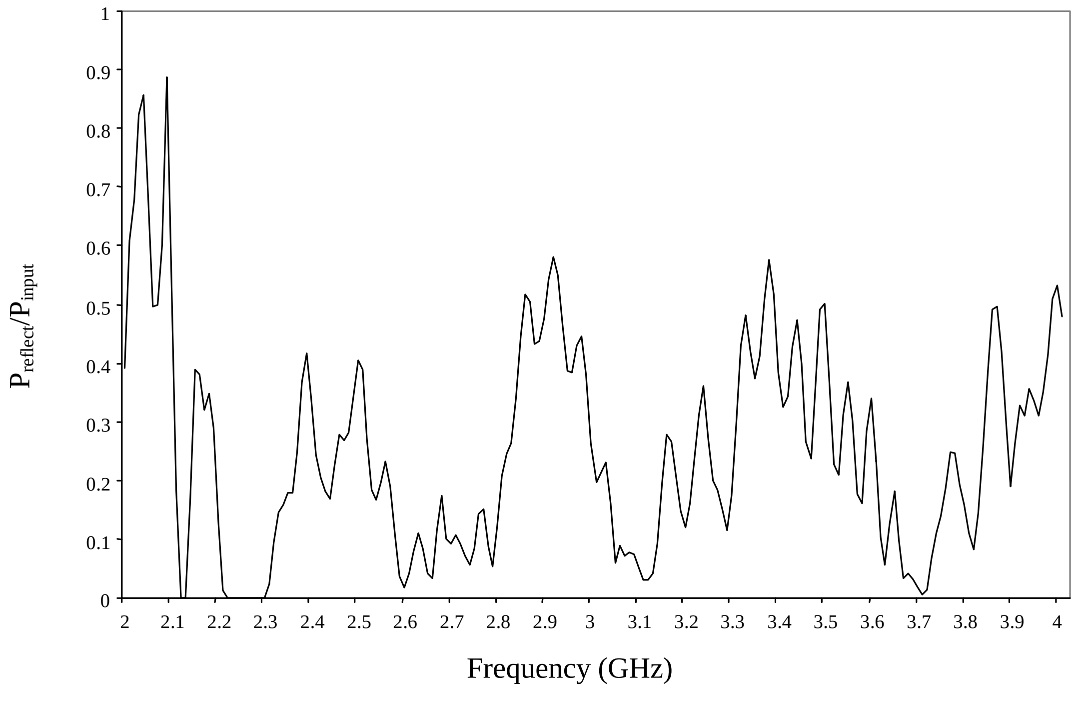

Figure 5. Percentage of Reflected Power vs. Frequency.

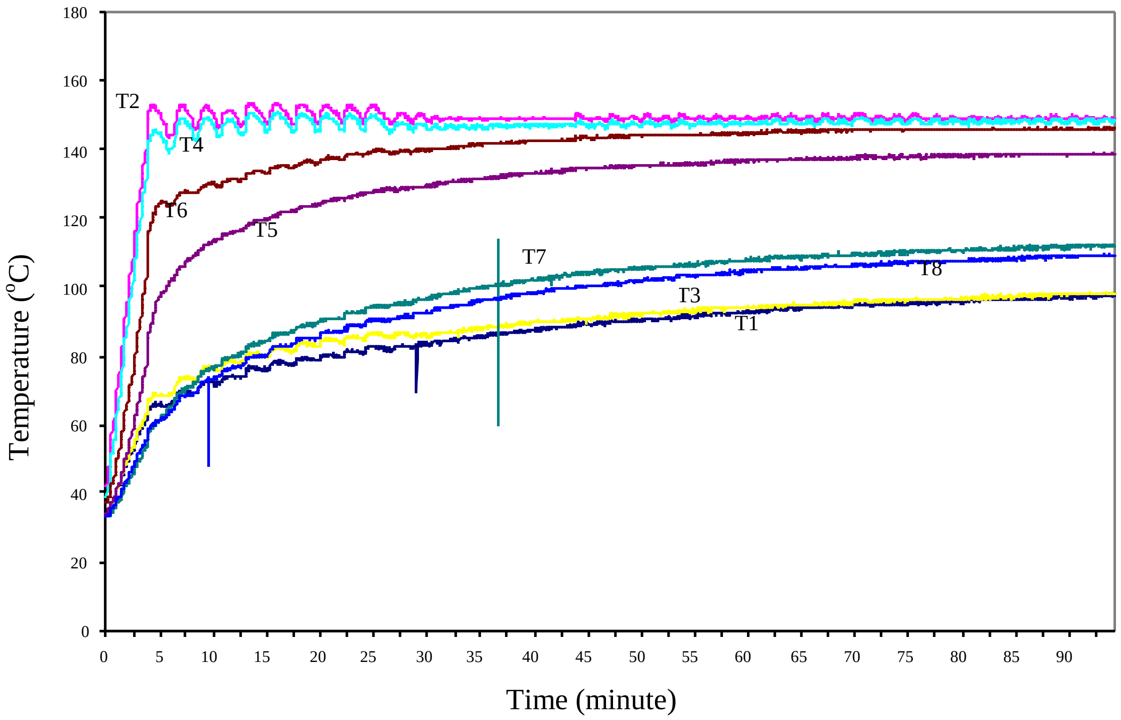

Figure 6. Single Mode Heating at f=2.5737 GHz.

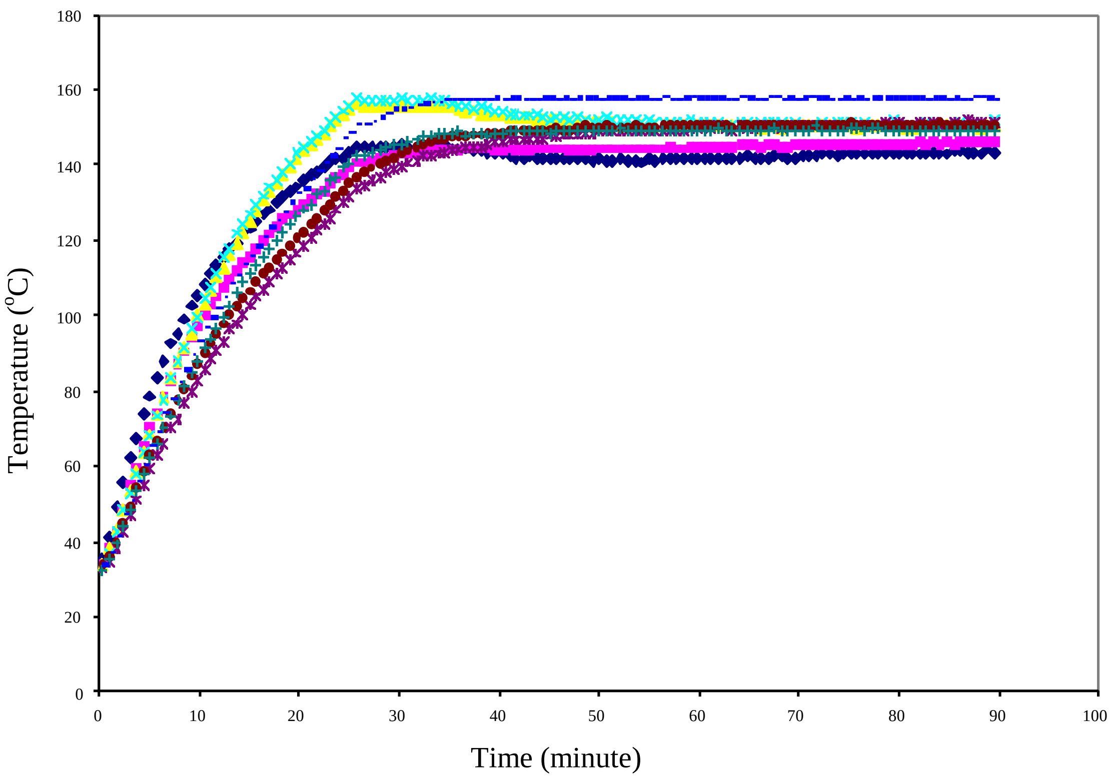

Figure 7. Single Mode Heating at f=3.0818 GHz.

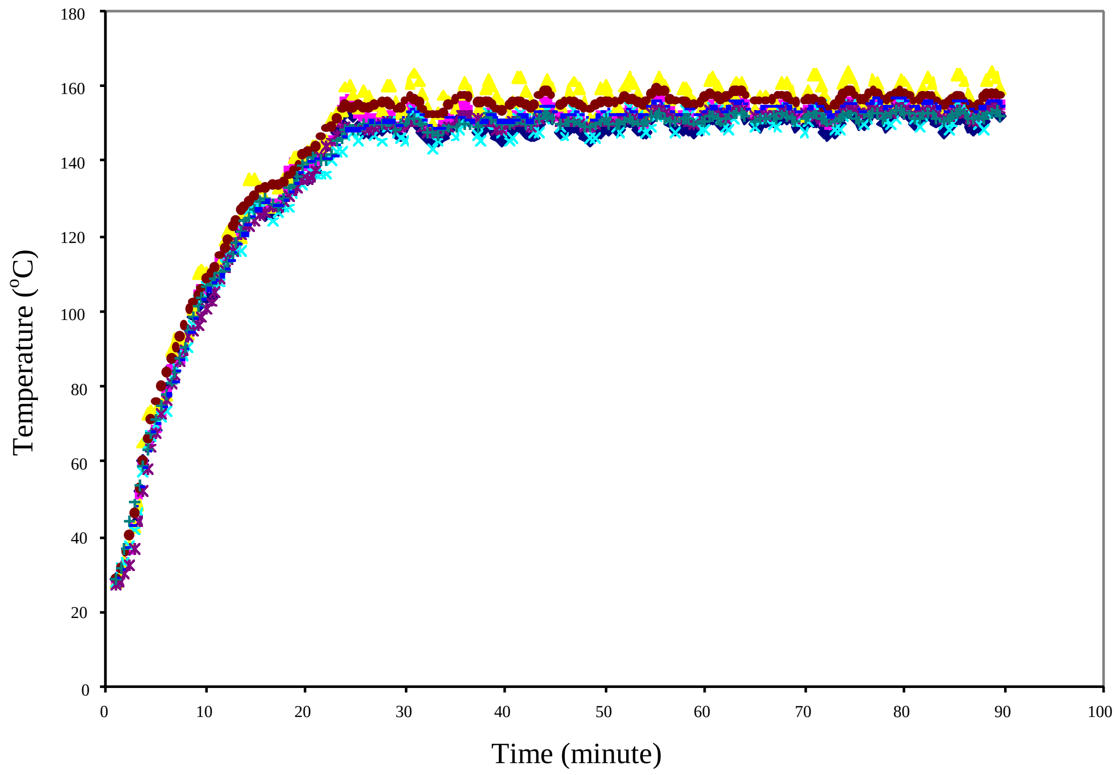

Figure 8. Mode Switching Heating.

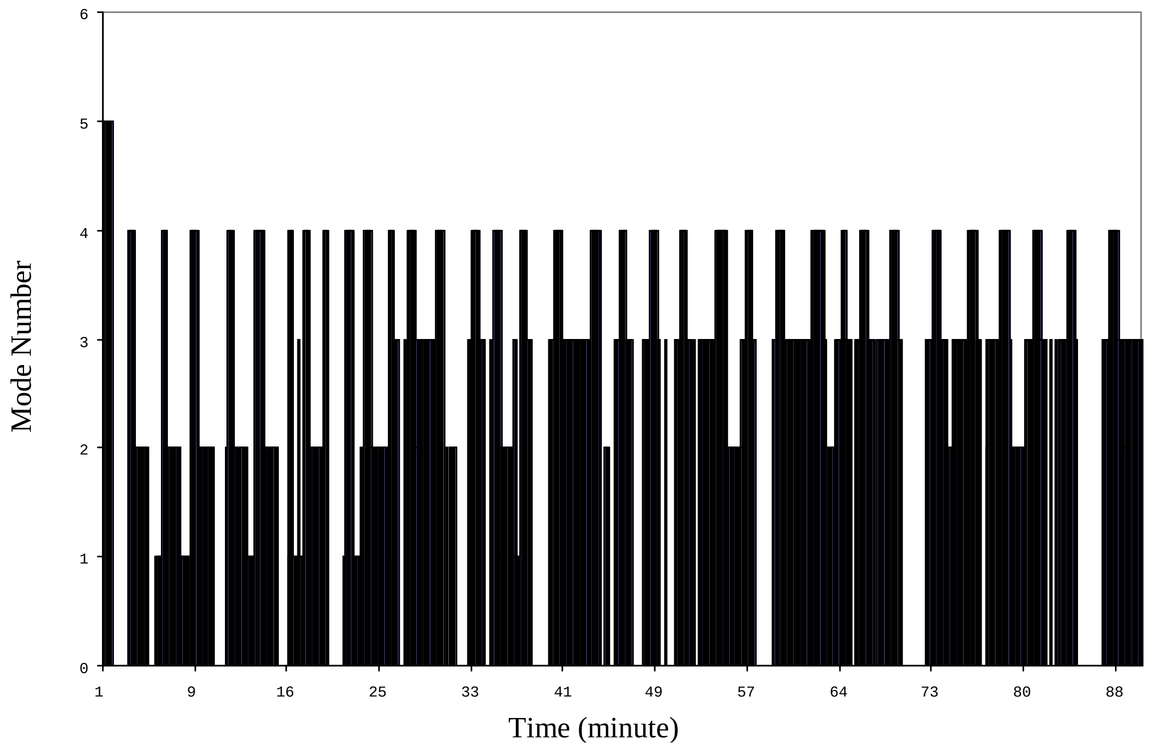

Figure 9. Mode Changes During Processing.

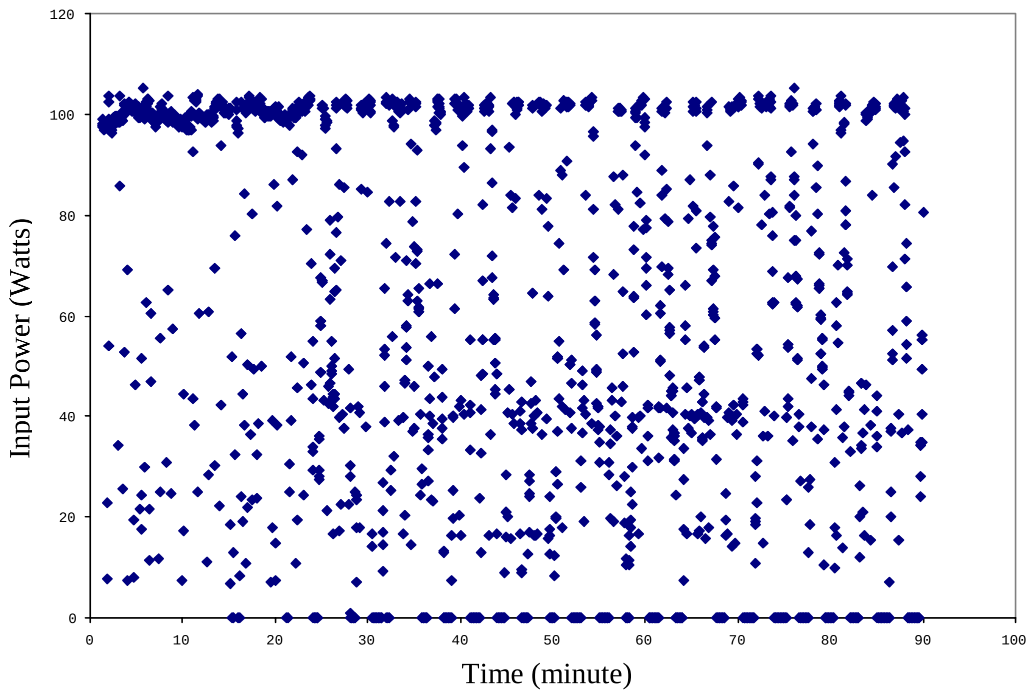

Figure 10. Input Power Change During the Processing.

Since the heating characteristics of the modes were determined before the processing, the success of mode switching technique in alleviating thermal gradients proved that the heating characteristics are repetitive. The effectiveness of power control algorithm can be seen from single mode heating profiles. PID algorithm was also studied but resulted in less stable temperature control. The parameters of PID controller needed to be optimized empirically for each mode.

Flexural strengths of the cured samples were tested for both single mode heating and mode switching heating experiments. The test method used was ASTM D790 3-point flexural test with a support-to-depth ration of 16. The results are listed in Table 2. Samples cured by mode switching heating showed better flexural strengths than those cured with single mode heating. As a conclusion, more uniform heating renders better flexural properties.

TABLE 2. Flexural Strengths of Microwave Cured 24-ply 3”by 3” Unidirectional Graphite/Epoxy Composites

Heating Method	Single Mode at f=3.0818 GHz	Mode Switching
Flexural Strength (psi)	116,288 ± 6,476	126,079 ± 13,038

CONCLUSIONS

24-ply unidirectional 3" by 3" graphite/epoxy composite parts were successfully processed using an automated variable frequency single mode cavity microwave processing system. Heating experiments proved that the heating characteristics of each mode is repetitive as long as the sample is loaded in the same way. Mode switching heating resulted in much improved temperature uniformity, hence the flexural properties of the product were improved with this strategy. The power control algorithm was proved to be effective and more stable than PID control. Further studies need to be carried out so as to improve the temperature uniformity and stability at the curing stage.

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