STATUS OF MICROWAVE ADHESIVE BONDING RESARCH

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Abstract

Microwave adhesive bonding has resulted in significantly shorter bonding times and stronger bonds for some systems. Compared to single mode microwave adhesive bonding, variable frequency mode-switching microwave adhesive bonding was applied to obtain uniform heating in microwave adhesive bonding of large-size materials. A new method was developed to monitor in situ microwave adhesive bonding of large samples. Process control programs were developed to intelligently control the microwave adhesive bonding process.

Introduction

Microwave processing of advanced materials has been studied as an attractive alternative to conventional thermal processing. The observed advantages include volumetric (inside-out) heating, direct and fast heating, high selectivity, and high controllability. For most conventional adhesive bonding applications, parts are heated with conduction or convection. The production cycle is long due to the difficulty in heating poor thermal conductors like polymers. This problem can be solved with microwave radiation. Since microwave heating is strongly dependent upon the magnitude of dielectric properties of the constituents, microwave energy can be applied in different processes to perform either volumetric, surface or selective heating. There are several potential applications of adhesive bonding in industry that could utilize the selectivity and rapidity of microwave heating. In the automotive, marine and aerospace industries, adhesive bonding of polymers and composites has been developed as one of the leading joining alternatives. In adhesive bonding, the polymer or composite parts have low loss factors relative to the adhesive material at the interface. Microwave energy is then directly transferred into the interface and cures the adhesive extremely rapidly, even though the substrate materials are very thick. This technique allows selective and instantaneous heating of the adhesives and reduces the bonding cycle significantly [1-4]. At the same time, microwaves produce bonds with mechanical and physical properties equal to or even higher than that of thermally bonded assemblies. Extensive study has been done in microwave adhesive bonding in Michigan State University.

Single Mode Microwave Adhesive Bonding

Single mode microwave method refers to the process that only one mode is used throughout the processing. The major objectives of this research are to study the feasibility of microwave adhesive bonding in a single mode applicator and to study the relation between electromagnetic field patterns and heating characteristics. Commercial substrate and adhesive materials were used because of the established knowledge of good adhesion and good mechanical properties. In adhesive bonding, compatibility between the substrates and the adhesive is required. Epoxy adhesive was selected because of its compatibility with a wide range of substrate materials. The epoxy adhesive used for this study was Eccobond A401-37 (epoxy based) from Grace Specialty Polymers. Because of its low dielectric properties, Bexloy W502 (glass reinforced ethylene/methacrylic acid copolymer) from Dupont was selected as the substrate for the preliminary microwave adhesive bonding study**.** The dielectric properties of both materials were listed in Table 1.

The operating frequency used in this study was around 3.725GHz. Due to the slight difference in sample size and position, the resonant frequency shifted slightly each time. To understand the electric field distribution pattern inside the single mode cavity, the electromagnetic mode (TMnpq or TEnpq) at around 3.725GHz was diagnosed. The method of mode diagnosis is explained in detail in [5]. Among the EM modes with resonant frequencies close to 3.725GHz in the empty cavity, the only mode with the characteristics was TM022. The resonant frequency of TM022 mode in the empty cavity was 3.756GHz.The resonant frequency in the loaded cavity was 3.723GHz. Thus the resonant frequency shifted down slightly (around 0.9%) when the small sized materials were loaded into the cavity. This is consistent with the theory that an increase in the dielectric constant leads to a decrease of the resonant frequency [6].

The sample was heated from room temperature to the bonding temperature in 3 minutes and then isothermally bonded at 120°C for 9 minutes. Thermally bonded assemblies were also prepared under normal pressure for comparison purposes. Samples were bonded at 120°C in a thermal oven for up to 180 minutes. The bonding results(Table 2) showed that microwave method reduced the bonding time and enhanced the bonding strength compared with thermal method.

The difference in bond strength between microwave and thermal methods is related to the break pattern in the single lap shear test. With sufficient bonding time, microwave bonded assemblies at different temperatures all broke within the substrates. This phenomenon indicates that the bond was stronger than the substrate material itself in microwave process. Thermally bonded assemblies all broke at the interface, indicating that the adhesion between the substrates and the adhesive was not strong enough.

Variable Frequency Mode-Switching Microwave Adhesive Bonding

the variable frequency mode-switching method was applied to obtain uniform heating in microwave adhesive bonding of large-size materials in a single mode applicator and improve the energy efficiency in multi-mode applicator. In a variable frequency system, the frequency can be varied to change the modes electronically which help the rapidity and controllability of the process control. The main objective of this research is to design the variable frequency mode-switching based on theoretical mode patterns, verify the heating uniformity of this approach and compare the variable frequency mode-switching with single mode and thermal adhesive bonding. In this research, the materials used were Bexloy W502 (major component: glass reinforced ethylene/methacrylic acid copolymer) as the substrate and Eccobond A401-37 (epoxy based) as the adhesive which were same as the part one. In addition, a nylon 6 and ethylene/methacrylic acid copolymer substrate (Surlyn SG201U) is also used with the Eccobond adhesive. The complex dielectric constant of Surlyn SG201U is 2.30-j0.008.

A large number of modes were available in the cavity at different frequencies. Most of the modes should have different heating patterns, though some of them could have similar heating patterns. The availability of modes with various heating patterns made it possible to select modes with complementary heating patterns to obtain time-averaged uniform heating. In our research, the modes TM020 and TM212 form one of the possible mode combinations with complementary heating patterns. The resonant frequency was around 2.84GHz for TM020 and 3.38GHz for TM212**.** Adhesives were heated up from room temperature to 120°C in 8 minutes and then maintained at a constant level. Adhesive temperatures were measured at 5 different locations across the adhesive. The temperature profiles were showed in Fig1. The maximum and average adhesive temperatures were 120°C and 115°C, respectively. The maximum temperature gradient was within 10°C. Panel materials were not substantially heated up and microwaves were concentrated at the adhesive curing and interfacial bonding region.

Mode-switching microwave curing was much faster than thermal curing as can be seen in Table 3. The maximum standard deviation of the extent of cure was 9.0% for both microwave 110°C and 120°C. The average standard deviation was 3.9% for 110°C and 3.6% for 120°C. The uniformity of mode-switching microwave heating was acceptable.

From Table 4, For Eccobond/Bexloy Assembly system, the strength of microwave bonded samples was significantly higher than thermally bonded ones. Microwave bonded assemblies all broke in the panel, indicating that the bond was stronger than the substrate itself. Thermally bonded samples all broke at the interface.

Table 5 shows that microwave bonded assemblies at 100°C for 45 minutes obtained the same strength as thermally bonded assemblies at 120°C for 100 minutes. Both microwave and thermally bonded assemblies broke in the substrates in single lap shear test. Since the interface and adhesive were stronger than the substrates for both microwave and thermally bonded assemblies, it was uncertain whether there was microwave enhancement of the adhesion between the adhesive and the substrate for the Eccobond/Surlyn assembly.

In Situ Monitoring of Variable Frequency Microwave Processing in a Single Mode Cavity

In order to reduce the amount of experiments and to realize intelligent processing, a new method needs to be developed to monitor in situ microwave adhesive bonding of large samples In a single mode cavity, resonant frequencies shift due to changes in material dielectric properties. The operating frequency needs to be constantly tuned to maintain the resonant state inside the microwave cavity. The resonant frequency shifting, which reflects the change in dielectric properties, can be used to monitor on-line the microwave processing. In variable frequency mode-switching microwave processing in a single mode cavity, resonant frequencies shift due to changes in material dielectric properties. The operating frequency needs to be constantly tuned to maintain the resonant state inside the microwave cavity. The resonant frequency shifting, which reflects the change in dielectric properties, can be used to monitor in situ the microwave processing. This new on-line monitoring technique was described in detail in [7] (patent application in process). The method can be applied in the microwave processes that involve changes of material dielectric properties in a single mode applicator.

Process Control System for Microwave Adhesive Bonding

The process control system was developed at the beginning of this research and implemented throughout the research. The process control system was first developed for single mode microwave adhesive bonding and then implemented for mode switching process to obtain uniform heating for large size materials. Existing hardware configuration was used in variable frequency microwave adhesive bonding process. Software was programmed in LabVIEW for cavity characterization, data acquisition and process control. The software for microwave adhesive bonding process includes two main programs. One is cavity characterization before bonding to obtain the mode spectrum, the other is process control during bonding to achieve uniform and stable bonding with on-line monitoring feature. The process control program is composed of a number of sub-programs, including data acquisition, mode switching, power and on-line monitoring controllers. In data acquisition, the temperatures of the materials and the incident and reflected microwave powers are obtained through an A/D board and then fed back the process controllers. The objective of mode switching is to obtain uniform heating by switching among modes with complementary heating patterns. The objective of the power controller is to keep the heating rate below maximum void free value during the adhesive heating up and maintain the temperature at constant value during isothermal bonding. The objective of the on-line monitoring controller is to determine the bonding cycle. Heating rate was adjusted with an on-off control algorithm. Isothermal temperature was controlled with the traditional PID algorithm. The PID parameters were obtained based on control theory.

Conclusion

Microwave adhesive bonding has resulted in significantly shorter bonding times and stronger bonds for some systems. Variable frequency mode-switching microwave adhesive bonding was applied to obtain uniform heating in microwave adhesive bonding of large-size materials. The maximum standard deviation of the extent of cure was 9.0% for both microwave 110°C and 120°C. The average standard deviation was 3.9% for 110°C and 3.6% for 120°C. The uniformity of mode-switching microwave heating was acceptable. Variable frequency system also helps establish in situ monitor microwave adhesive bonding of large samples. Finally, process control programs were developed which were implemented throughout the research.

Reference

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Table 1. Dielectric Properties of the Materials

			Dielectric Constant ε′	Dielectric Loss Factor ε″
Adhesive	Eccobond A401-37 (epoxy based)	Uncured	4.10	0.307
		Fully cured	2.58	0.029
Substrate	Bexloy W502 (ethylene copolymer) Panel		2.11	0.006

Table 2. Shear strength of microwave or thermally bonded assemblies

Bonding Conditions	Break Pattern	Shear strength
Microwave 3 min heat-up, 9 min isothermal bonding at 120°C	Shear in Panel	From 794 to 810psi (average 801psi)
Thermal 180 min at 120°C	Shear at interface	From 451 to 637psi (average 537psi)

Table 3. Comparison between Mode-Switching and Thermal Curing at Different Temperatures

Curing Conditions	Microwave Process of 6 min heat up and then isothermally at 110°C	Microwave Process of 8 min heat up and then isothermally at 120°C	Thermal Process of 30 min heat up and then isothermally at 110°C	Thermal Process of 40 min heat up and then isothermally at 120°C
Total Required Heating Time	30 min	20 min	120 min	100 min
Ultimate Extent of Cure	97.4%±1.0%	98.5% ±1.0%	95.4%±0.2%	98.8% ±0.4%
Maximum Standard Deviation Of Extent of Cure	9.0%	9.0%	3.1%	3.8%
Average Standard Deviation Of Extent of Cure	3.9%	3.6%	1.1%	1.6%

Table 4. Comparison of Bond Strength of Microwave and Thermally Bonded Assemblies (Eccobond/Bexloy Assembly)

Bonding Cycles	Break Pattern	Shear Strength
Microwave 6 min heat-up, 24 min isothermal bonding at 110°C	Shear in Panel	5.87MPa ± 0.84MPa
Microwave 8 min heat-up, 12 min isothermal bonding at 120°C	Shear in Panel	5.80MPa ± 0.79MPa
Thermal 30 min heat-up, 90 min isothermal at 110°C	Shear at interface	2.85MPa ± 0.43MPa
Thermal 40 min heat up, 60min isothermal at 120°C	Shear at interface	3.23MPa ± 0.46MPa

Table 5. Comparison of Bond Strength of Microwave and Thermally Bonded Assemblies(Eccobond/Surlyn Assembly)

Bonding Conditions	Break Pattern	Strength of the Assembly (MPa)
Microwave at 100°C for 45 minutes	Shear in Panel	6.14±1.02
Thermal at 120°C for 100 minutes	Shear in Panel	6.06±0.48

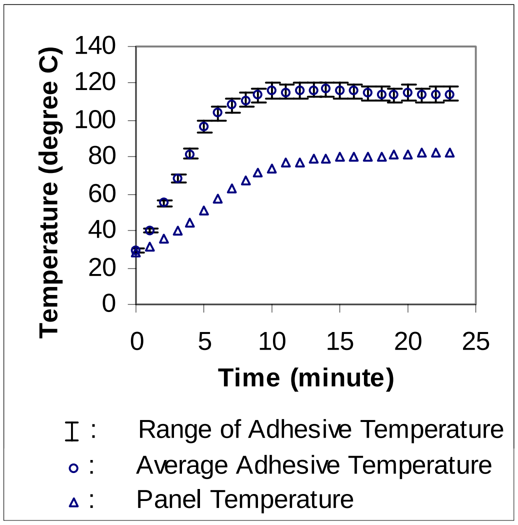

Figure 1. Temperature Profiles of Mode-switching Microwave Adhesive Bonding

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