Energy Efficient Solid-State Microwave Curing of Carbon Fiber Reinforced Composites

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***Abstract*—In this paper we present a new set-up for curing carbon fiber composite materials realised around four solid state power amplifiers generating 250 W microwave power in the frequency range 2.4 - 2.5 GHz. This microwave curing set-up improves the homogeneity of the heating pattern by combining different standing waves in a process using an IR camera, as feedback for a machine learning based controller. We show also that the energy used for the curing process is drastically reduced in comparison with curing using conventional methods.**

***Index Terms*—Industrial applications, Microwave, Solid-state, Chemical applications, Scale-up.**

I. INTRODUCTION

Carbon fiber reinforced polymers (CFRPs) are high strength, high modulus, low density but relatively priced composite materials. Presently as they are in high demand for the aerospace and automotive industries, fast and energy efficient manufacturing techniques are highly sought after. Conventional curing methods, such as autoclave and oven curing rely on convective heating, where not only the medium surrounding the composite materials has to be heated but also the whole body of the oven is heated. Using microwaves for curing CFRPs has the advantage to heat only the composite materials. This is often attributed to the composites ability to volumetrically absorb electromagnetic energy within the GHz region [1]. The advantage over autoclave and oven curing processes are essentially a decreased curing time and high energy savings [2] [3] [4].

II. PHYSICAL SETUP

We have developed a microwave curing set-up for CFRPs, using a system composed of four solid state microwave power amplifiers, based on the NXP (now Ampleon, Netherlands) quad channel radiofrequency (RF) power generation system. Each channel is composed of a BLAZE 250 power amplifier module, composed of an LDMOS driver, of the type BLF2425M9L(S)30 and a main power amplifier, of the type BLC2425M8L300P. The RF generation and control system board includes four BLP25RFE001 chip-sets. Each chanel delivers 250 Watts between 2.4 and 2.5 GHz into a rectangular multi-mode cavity, with dimensions: 400 mm x 400 mm x 135 mm as shown in Fig. 1. The targeted CFRP composite material with dimensions 150 mm x 250 mm is placed in the center of the cavity, at 30 mm from its bottom, where the E field shows maximal values. Microwave processing is known for its non-uniformity, inevitable presence of hot spots and thus a strong potential non-uniform curing. Therefore, we are using an ensemble of complementary standing waves, as to homogenise the heat distribution. Our implementation is based on a real time IR camera feedback, allowing the selection of the standing waves that complement each other and lead to heat homogenisation. The four generators are set at the same frequency, and the frequency is swept in the interval of frequencies considered while phases are set in increments of 10° phase differences in between ports. Four coaxial to waveguide transitions are used as feeders to the cavity and their orientation is central on each of the sides of the cavity. The coupling to the cavities' modes is assessed and a selection of frequencies resulting in the lowest reflection coefficients is made prior to injecting high power. The solid state generation of microwaves provides unique benefits, as compared to the traditional magnetron generators, as it is only this type of generation that provides the capability to realise the manipulation of the standing waves, i.e. using the differences in phases in between ports and multiple frequencies to excite different standing waves and realise heat homogenisation.

III. EXPERIMENT

CFRPs consist of a binding matrix, often some kind of thermoset polymer such as epoxy, and a reinforcement, such as carbon fibers. When the impregnation occurs before curing, the uncured CFRP sheets are referred to as pre-pregs and can either be unidirectional or woven [5]. In order for the polymer to cure the CFRP needs to be held at the curing temperature (also referred to as dwell temperature) for a certain dwell time. For our experiments, the CFRP samples were made from sheets of HexPly©8552 unidirectional (UD) carbon pre-pregs. These uncured pre-preg materials are placed in a vacuum bag for further processing, as shown in Fig. 2 and

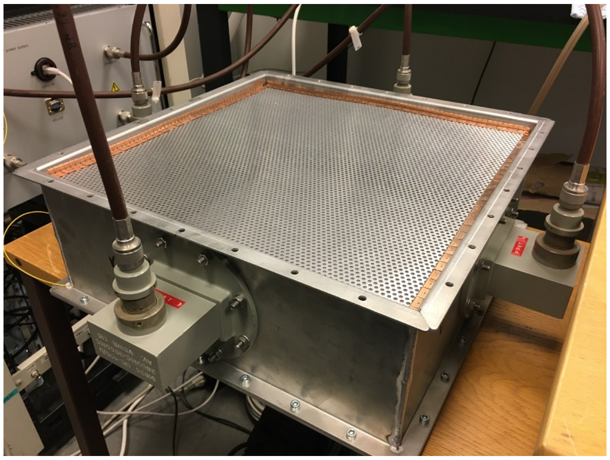

Fig. 1. Experimental setup showing the microwave heating system.

then cured using microwaves at around 180°C.

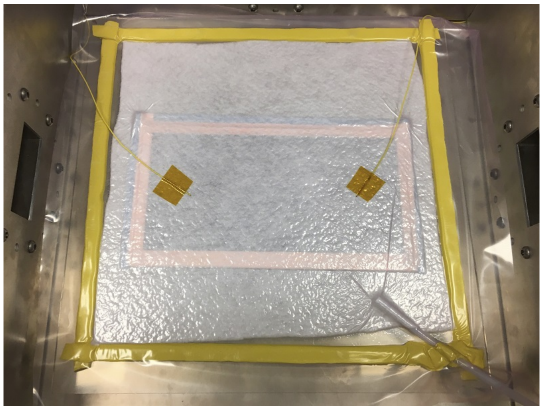

Fig. 2. Vacuum bagging only process

IV. RESULTS

The microwave-cured UD samples were tested using a three-point bending test was performed to investigate the flexural properties of the samples. The test was performed in accordance with the ASTM D790 standard test method [6]. The reference samples of the CFRPs were cured in a Memmert Universal Oven UF450plus industrial oven also using the vacuum bagging technique. The results showed that by using the microwave curing process on unidirectional CFRPs it is possible to reduce the curing time (excluding cooling time) by up to 89% and the energy consumption by up to 90% compared to oven curing. In addition to the increased efficiency, all of the microwaved-cured unidirectional CFRPs showed a higher stiffness than the oven-cured unidirectional CFRP, without showing a considerable reduction in maximum stress. The increased stiffness did however come at an expense of a reduced maximum strain. The results presented in Fig. 3 show that the microwave curing process significantly reduces the energy consumption compared to the oven curing process. This is specially the case for a heat process in a ”sawtooth” profile, as presented in this figure, characterised by an excursion at 180°C followed by a cooling down till 140°C during 5 min and repeated consecutively during the whole duration of the curing time. One of the distinct differences between the microwave and oven curing process is the time needed for the ramp-up phase. It can also be concluded that all microwave-cured samples showed higher Young’s modulus than the oven-cured sample. Thus, the microwave curing process was more energy efficient and yielded samples with higher stiffness than the oven curing process.

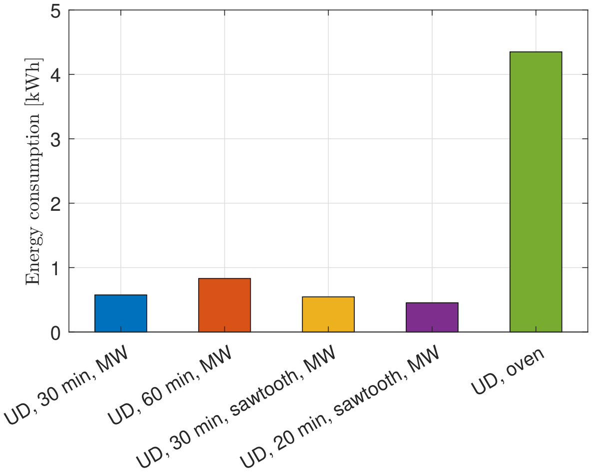

Fig. 3. Estimated energy consumption during microwave and oven curing processes.

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