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Evaluation of eddy current testing for quality assurance and process monitoring of automated fiber placement

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ABSTRACT

Standards in energy and cost efficiency are higher the ever especially in the aerospace industry. While structures made from carbon-fiber reinforced plastics (CFRP) show significant advantages in regards to specific strength and lightweight design, further improvements in their production processes are essential in order for CFRP to be competitive in the future. The authors present eddy current (EC) testing as a means for quality assurance (QA) and process monitoring for CFRP parts produced by automatic fiber placement (AFP), which is one the most prevalent production methods in aerospace industry. Eddy current testing shows the potential for highly automated process monitoring that can reduce error correction and cycle time in AFP.

1. General introduction

The importance of carbon fiber reinforced composites (CFRP) has increased steadily in the past years [1] and market projections expect a further growth of this particular segment with rates as high as 17% p.a. by the year 2020 [2]. However, this market growth may only be achieved, if the relative cost of CFRP parts can compete with their metal counterparts. Since savings potential in raw material is limited, innovation should chiefly focus on the production process itself [2].

Aerospace is a key industry for CFRP parts. Production rates for the Airbus A350 XWB are planned to be as high as 13 planes per month with over 50% of the structure being made from CFRP. Most of the fuselage parts are produced using automated fiber placement [3]. In order to fulfill high production rates and still maintaining economic efficiency further improvements in process automation in AFP are necessary [4]. In addition, production processes will benefit from reliable techniques for quality assurance (QA) by means of reduced cycle time and reduced scrap rates.

Currently, a number of manufacturers are developing optical systems for the purpose of inline quality control during the AFP process [4]. For example, by measuring the actual fiber orientation of the layup, several defects, including gaps, overlaps, twisted tows and contamination with foil or fuzzballs, may be detected, since sudden changes in fiber orientation indicate these defects [5]. Thus, fiber orientation can be employed as a criterion for QA. The disadvantage of optical systems, though, is that their use is limited by the surface qualities of carbon fiber prepreg. Since the carbon fiber laminate shows little visual contrast, intricate systems are needed for illumination [6]. Furthermore, on rough surfaces, like those exhibited on some prepreg materials, the optical system will not be able to measure the fiber orientation at all.

In this study high frequency eddy current (EC) testing is being analyzed as a means for quality assurance of AFP parts. As EC testing is based on electric and dielectric material properties the detrimental surface effects observed in optical quality control can be avoided. For this purpose, two different kinds of specimens were tested. First, a set of cured plates with different defects was crafted to evaluate the EC techniques for non-destructive testing (NDT) purposes. The results of these tests were then compared with the results produced earlier by Schulze et al. [8]. Second, tests were carried out using uncured prepreg material to examine the use of EC testing for on-line quality assurance in layup processes. This paper will discuss the results of these tests and provide suggestions for how eddy current tests might be implemented in AFP processes in the future.

2. Experimental setup

2.1. Eddy current testing device

All measurements were performed using the SURAGUS EddyCus Multi Parameter Eddy Current Scanner (MPECS). With this eddy

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current testing device local changes in electric impedance can be evaluated and represented in the form of C-scans. It is possible to simultaneously run tests with four discrete frequencies ranging from 10 kHz up to 100 MHz. Among other applications the EddyCus MPECS was developed to test raw carbon fibers and non-crimp fabrics [9,10]. The device has also been used for QA of CFRP where various defects such as delaminations, fiber cracks, undulations and impact damages were detected in depths of up to 7 mm [11].

The scanner utilized was mounted on a Cartesian robot with three axes (see Fig. 1). The two horizontal axes may be controlled during testing, while the vertical *z*-axis functions as an in-feed axis which assures a constant distance between scanning probe and specimen. As a result, test subjects for the EddyCus MPECS are limited to flat specimens of about 300 × 400 mm. Scanning with the EddyCus MPECS is performed as a series of point measurements of the electric impedance. Theoretically, measurement speeds could be as high as 70 mm/s while the spatial resolution of the scanner could be as low as 20 μm [9,11]. These point measurements were processed by an imaging algorithm, which constructed a C-scan based on the measurement data.

The EddyCus MPECS can be equipped with several different eddy current probes. For this series of experiments, tests were conducted using a high-frequency absolute probe (HF), a differential probe and a half transmission probe (HT) (see Fig. 2). Absolute probes consist of an excitation coil and a receiver coil combined in a single sensor. These probes measure the absolute voltage induced in the receiver coil. Typical applications include layer thickness measurement as well as material characterization. The differential probe is built of two absolute probes which are connected so that their measurement signals cancel each other out as long as their magnetic fields are undisturbed. Testing with the differential probe therefore is based on the comparison of two separate sensors resulting in highly sensitive and anisotropic probe. HT probes represent a special kind of absolute probe in which the excitation and the receiver coil are spatially separated. Due to this separation high excitation currents may be applied, thereby enhancing penetration depths. HT probes also show significant anisotropic behavior [9,12–14,17].

2.2. Test specimens

The material used for all specimens was 150 mm wide toughened-epoxy prepreg HexPly 6376 by Hexcel. This prepreg contains 12 k HTS carbon fibers and is 0.25 mm thick in the uncured state. Hexply 6376 is mainly used in the fabrication process of primary aircraft structures and is therefore designed for high impact resistance and damage tolerance [15].

Testing consisted of two experiments with multiple series. For the first series of the experiment, four plates with a thickness of about 4.4 mm and 18 plies each were laminated by hand and subsequently cured in an autoclave at 10 bar ambient pressure and 180 °C curing temperature. Three of the plates contained defects: one made from steel foil, one from 0.1 mm thick PTFE and one from fuzzballs. The forth plate was free of defects. Fig. 3 shows the fiber orientations and defects which were inserted during manual layup. These plates were scanned from underneath. As a result, the first defect appeared in the second layer.

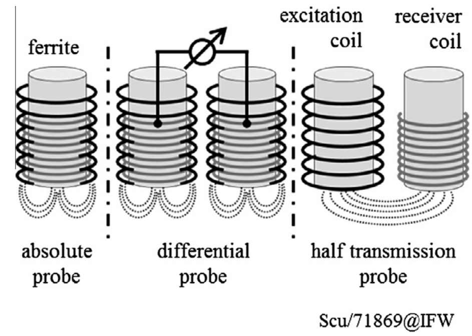

Fig. 2. Eddy current probes.

A second series was conducted using uncured prepreg material, thus simulating the layup process by an automatic fiber placement machine. For the first experiment, four layers of uncured prepreg with an area of 70 × 70 mm were manually laminated. Given the thinness of the prepreg layers the EC probes had to be shielded from the metal casing of the Cartesian robot. Therefore, the material was laminated on a mold made from 20 mm thick PUR (see Fig. 4). However, a small aluminum inlay was inserted in one quadrant of the mold to simulate the influence of a metal, tape-laying mold on resulting eddy currents.

In the second experiment, a smaller scanning area was chosen and additional material is laid up on the first four layers exclusively above the metal inlay. This made it possible to determine up to which material thickness the metal below could still be detected.

Following this, a new layup was laminated on the mold to determine the scanner's ability to detect gaps and overlaps in freshly-laid material. Eight single stripes of prepreg were arranged on a ground layer of material to fashion gaps ranging from 1 to 3.5 mm and overlaps ranging from 1 to 5 mm (see Fig. 5).

2.3. Experimental procedure

First, scans were performed with the cured specimens. The focus of this analysis is to assess the suitability of the different EC probes for testing CFRP parts. Therefore, the penetration depth and resolution were evaluated at various scanning frequencies.

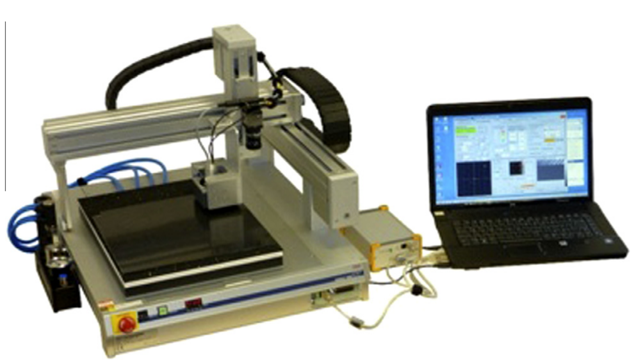
Fig. 1. SURAGUS Eddycus MPECS [7].

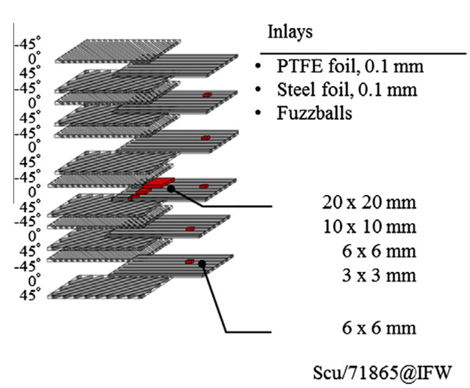

Fig. 3. Layup of plates.