Automatic Fiber Placement (AFP) Technology, Actual State and Future Improvement through Using NDT (Ultrasonic) Equipment in On-line Processing

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Abstract. In this paper are presented all of the technologies used for research at the Institute for Advanced Composites and Robotics (IACR). Focus is put on the automated fiber placement (AFP) technology and the equipment used to perform this technology. Analysis presented, refer to possible mistakes in the final product, composite part intended to be a primary structure of an airplane, due to the inability to know the influence of the compacting roller, or the characteristics of the prepreg on the occurrence of micro voids in the laminate of the part produced. As a response to this acknowledgement, preliminary research is done at IACR where ultrasonic sensor is used for nondestructive testing (NDT) in composite materials. This preliminary research has shown that it should be further inspected whether ultrasonic sensor following the compacting roller, could improve the impacting process and diminish the number of voids in the final product.

Keywords: IACR, Mikrosam, automated fiber placement (AFP), filament winding (FW), prepreg making, composites, voids(pores), NDT, ultrasonic sensor

1 Introduction

The research on which is based this paper is conducted at the Institute for Advanced Composites and Robotics (IACR), which is one of the very few institutes in the world, and only one in the region, that conducts research in this particular field. The institute is founded in 2009, by Mikrosam, Macedonian company which is a leader in the region, and among the best in the world in the composite machine industry. It is the only company that has developed the entire technology for producing composite products – prpereg making machine, filament winding machine and fiber and tape placement machine. As a result of this, IACR is equipped with the best composite technology which is an advantage that guarantees probably the most valid research in the field of composites. IACR offers comprehensive analysis and testing, done in many of its laboratories for: software development, software engineering, motion control, chemical and mechanical composite research, data acquisition and process control, and for developing technological process of modern composites. This paper work is produced as a summary of the analysis made on a specific issue occurring in the AFP technology, which could result in a joint initiative to find an innovative solution for the voids' occurrence problem in AFP, and could further be readapted for other applications. The work explained in this paper is based on more than 30 years of extensive experience and knowledge in the composites' field and on analysis done on a daily basis by mechanical, electro-technical, software and chemical engineers who develop and constantly improve the upper mentioned technologies.

2 Composite Technologies

Composite materials due to their advantageous characteristics are becoming the materials of the future. These materials, although long ago discovered and widely used by high-tech industries (aerospace, automotive, marine, space), in other industries are yet to be discovered. Their specific characteristics strength, stiffness, and "weigh saving"[1]make them dominant over other materials and expand their application range, from leisure and sports to industrial complex components. Therefore, composites technologies are one of the most expensive and even for engineers yet unfamiliar technologies. Following this perception, short overview of the core composite technologies will precede the case study in this paper.

2.1 Prepreg Making

Prepreg by itself is a kind of a semi-product, "combination of a matrix (or resin) and fiber reinforcement"[2]. Due to its good mechanical characteristics, easy processing and lower cost, prepreg is used in aerospace, railway, marine, energy and other industries.

There are two main methods to make prepreg: hot melt – through which can be produced fabric and unidirectional (UD) prepreg, and solvent – through which can only be produced fabric prepreg.

Hot melt method starts by coating the resin on a silicon paper in a thin film, and then impregnating it onto a fiber on the prepreg machine, under roller pressure and heat [3].

In the solvent method, resin is dissolved in a solvent and dipped onto a fabric [4]. Later, impregnated prepreg is exposed to heating oven to decrease the solvent content [5].

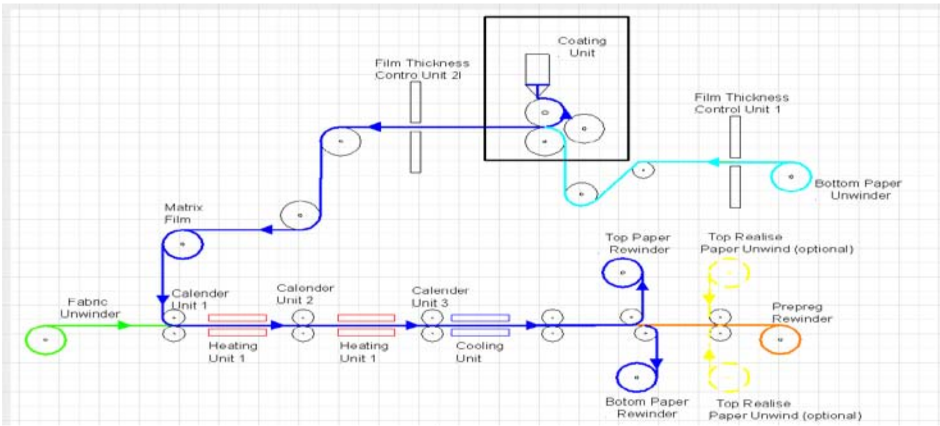


Fig. 1. Hot melt prepreg making method

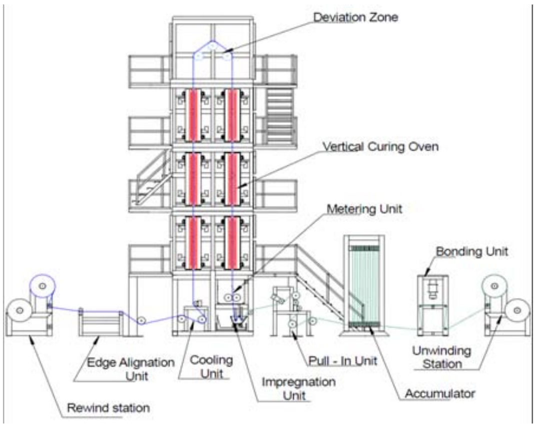


Fig. 2. Solvent prepreg making method

Fig. 3. Prepreg line -Type PLS-250-2F **Fig. 4.** Vertical impregnating machine LI 300
(Source: Mikrosam, cases, prepreg production [6])

2.2 Filament Winding (FW)

Filament winding is a composite technology used to make high-pressure vessels (LPG, CNG), oxygen tanks, compressed natural gas cylinders, underwater pipes. It is a process in which "continuous reinforcements in a form of rovings or monofilaments are wound over a rotating mandrel" [7]. Winding angles and placement of reinforcements are controlled by specially designed machines, and so spherical, conical, and geodesic shapes can be made. Cylinders made out of composite materials surpass the quality and cost of heavy metal cylinders.

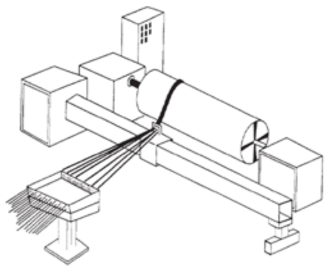


Fig. 5. Schematic of the FW process (Source: Suong V. Hoa[8])

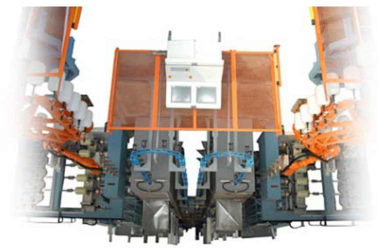


Fig. 6. Automated FW machine (Source: Mikrosam [9])

2.3 Automated Fiber Placement (AFP)

Fiber placement is a process similar to filament winding [10]. This method is able to fully exploit special and an-isotropic characteristics of the composite materials as a benefit of the freedom this production process gives to the designer.

Automated fiber placement (AFP) is an automated composites manufacturing process of heating and compacting resin pre-impregnated non-metallic fibers on typically complex tooling (mandrels). The fiber usually comes in the form of what are referred to as "tows". A tow is typically a bundle of carbon fibers impregnated with epoxy resin and is approximately 3.2 mm wide by 0.1mm thick and comes on a spool.

AFP as such contributes to high productivity, improved quality, and low cost for large composite structures. Through automation, the process of FP has improved in lowering manufacturing cost (labor, material scrap, better control)[11].

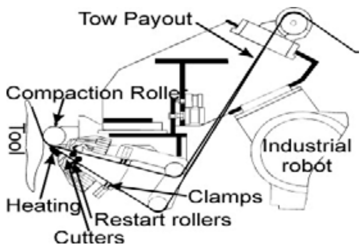


Fig. 7. AFP schematic (Source: Salman Khan [12])

Fig. 8. AFP machine (Source:Mikrosam [13])

3 Case study: Occurrence of Voids during AFP Process

3.1 NDT

In advanced technology applications such as aerospace, with industrial emphasis on economics and safety, it is critical to use and develop robust and practical composites' NDT methods. Composites' NDT encompasses a range of modified traditional and new tools including ultrasonic, x-ray, acoustic emission, thermal, optical, electrical and a variety of hybrid methods.

NDT stands for non-destructive testing. In other words, it is a way of testing without destroying. In today's world where new materials are being developed, older materials and bonding methods are being subjected to higher pressures and loads. NDT ensures that materials can continue to operate to their highest capacity without failing below the predetermined time limits. In addition, NDT can be used to ensure the quality right from raw material stage through fabrication and processing to pre-service and in-service inspection [14], [15].

The field of Nondestructive Testing (NDT) is very broad, interdisciplinary field that plays critical role in assuring that structural components and systems perform their function in a reliable and cost effective fashion. NDT technicians and engineers define and implement tests that locate and characterize material conditions and flaws that might otherwise cause planes to crash, reactors to fail, trains to derail, pipelines to burst, and a variety of less visible, but equally troubling events. These tests are performed in a manner that does not affect the future usefulness of the object or material. In other words, NDT allows parts and material to be inspected and measured without damaging them. Because it allows inspection without interfering with a product's final use, NDT provides an excellent balance between quality control and cost-effectiveness.

Nondestructive evaluation (NDE) is a term that is often used interchangeably with NDT. However, technically, NDE is used to describe measurements that are more quantitative in nature. For example, an NDE method would not only locate a defect, but it would also be used to measure something about that defect such as its size, shape, and orientation. NDE may be used to determine material properties, such as fracture toughness, formability, and other physical characteristics.

There are many NDT techniques/methods, which are used depending on four main criteria: type of material, type of defect, size of defect and location of defect. Therefore, it is important to choose the appropriate method[16].

Most Common NDT Methods are: Visual(optical and Laser), Liquid Penetrant, Laser techniques, Sherography, Holography, Radiography, Ultrasonic, Magnetic, Infrared thermography, Acustic Emission testing, Microwave technique

3.2 Ultrasonic Inspection

In ultrasonic testing, high-frequency sound waves are transmitted into a material to detect imperfections, or to locate changes in material properties. Most commonly used ultrasonic testing technique is pulse echo, whereby sound is introduced into a test object and reflections (echoes) from internal imperfections, or part's geometrical surfaces, are returned to a receiver. Below is given an example of composite part. High frequency sound waves are introduced into a material and they are reflected back from surfaces or flaws. Ultrasound inspection methods are powerful tools for nondestructive testing and are widely used in the industry because high resolutions are possible depending on the chosen frequency (100 kHz to 40 MHz). In ultrasonic testing, stress waves are injected into the material or component to be examined and then, transmitted/reflected beams are monitored. Ultrasonic measurements can determine the location of a discontinuity in a part or structure by accurately measuring the time required for a short ultrasonic pulse generated by a transducer to travel through a thickness of a material,reflect from the back or the surface of the discontinuity, and be returned.

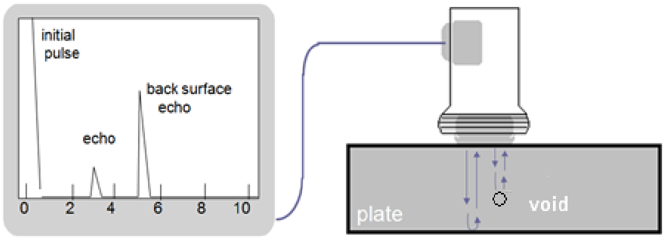


Fig. 9. (Example: use of noninvasive techniques to determine the integrity of a material, component or structure, or to quantitatively measure some specific characteristics of an object.)

Ultrasonic waves are used to evaluate the condition of a material, anomalies' absorption, or to deflect the sound waves, which are then detected as changes in the waves: holes, delaminations, voids; damage, debonds; resin-rich; poorareas

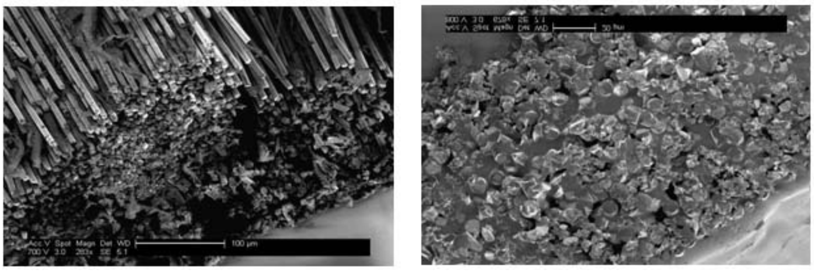
Our research suggests that we use these technologies to detect defects (pores) voids, in the process of placing the fibers through AFP technology.

3.3 Voids (Pores)

Presence of pores in the final product is a significant mistake in the technological process of work. Due to the inability to know the influence of the compacting roller, or the characteristics of the prepreg as factors that influence the occurrence of pores in the laminate in the final product, today at IACR preliminary research is done on the use of ultrasonic sensor as one of the methods for NDT. The method used to detect defects without destructing the material (the prepreg in this case) is one of the advanced methods used in the world. By placing ultrasonic sensors above the compacting roller on the AFP machine, pores (compressed air) in the laminate might be detected while placing. With this early air detection (while placing the fibers), certain parameters (pressure of the compacting roller, temperature of placement, and speed of placement) that influence pores occurrence might be changed. After this change is made, pores occurrence will be observed again. During the on-line processing, the quality of the final product will be improved and this will result in better mechanical characteristics of the final product material. With this practice, laminate voids and/ or improper track order might be observed, which will immediately signal to change the parameters in case there is a mistake that might result in a bad quality product.

Experiments and literature research show that the presence of more than 2-3% of pores in the final composite part has strong influence on the mechanical characteristics of a material [17], [18].

Below are given two SEM pictures with different % of pores in the sample examined. The 1st picture is an example of bad quality prepreg, and the 2nd is an example of a good quality prepreg, which needs to be used in the AFP process.



~ 10 % voids ~ 1,3 % voids

Fig. 10.

4 Solution – Improving the Characteristics of the Material

High number of voids in the material causes a problem on the forces that influence the final product. The aim of these methods is during the process of consolidation via sensors, defects (pores) to be early detected, impacting process to be improved, and the occurrence of voids in the final product to be decreased.

It is well known that void content of a composite may significantly affect its mechanical properties and therefore, it is an important indicator of composite’s quality. Interlaminar shear strength and void content of the consolidated parts are considered to be key quality indicators.

AFP processing for the on-line consolidation system is determined by adjusting the three system processing parameters: roller pressure, speed, and temperature. Therefore, this study focused on these three parameters, and was done in two steps. At first, a two-factor central composite design of experiments was used to define the combination of processing parameters, and next, void content was calculated (SEM images).

The inspection of final composite part (placement prepreg) is a time consuming and expensive procedure, mainly due to necessity inspection using conventional NDT methods. Therefore, the objective of this study is to develop an ultrasonic technique, suitable for placement of preperg and voids determination, without interrupting the process. The most promising technique which enables inspection at a relatively long range and can be used for inspection prepreg from an outside perimeter is based on ultrasonic guided waves. Guided waves can propagate long distances in planar and tubular structures, and have already been used for voids' inspection.

Our research anticipates that particularly in AFP, an ultrasonic sensor that will monitor the compacting roller, can have an impact on process improvement and voids' occurrence decrease in the final product.

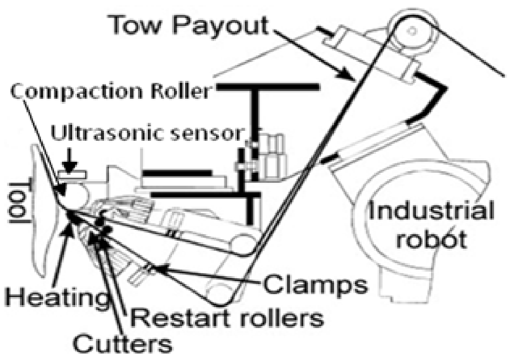


Fig. 11. (AFP with inserted ultrasonic sensor above the compaction roller)

5 Conclusion

Case study explained in this paper, and corresponding research made at IACR (in one of the most advanced composite materials laboratories), show that in order to acquire full advantage of the quality and cost saving of composite products, composite materials during the process of production have to be carefully inspected, examined and cured, to avoid troubles when they are transformed into final products. Since the fact that main cause for cracks, bursts, derails is the occurrence of voids in the laminate of the final product is not a novel issue, the idea of this paper is to initiate use of a different voids' inspection technology that will not require interruption of the production process (NDT). This technology is based on ultrasonic sensor which through guided waves would foresee possible voids, and simultaneously would give data on the parameters (pressure, temperature, speed) of the compacting roller that influence these cracks during the AFP process (as a process on which this research is focused).

Validity of this study lies in the expected results from the use of the proposed ultrasonic inspection technology, which suggests that being able to inspect and anticipate voids beforehand would mean high efficiency of the core composite technology, better quality of the composite final products, and competitive advantage for the producers and beneficiaries of these products.

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