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Procedia CIRP 62 (2017) 56 – 61

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10th CIRP Conference on Intelligent Computation in Manufacturing Engineering - CIRP ICME '16

Concept for automated production of CFRP-metal hybrid compounds integrated in an Automated Fiber Placement process

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Abstract

To solve the problem of load transmission into thin walled CFRP Structures, a new joining technology is being developed (Multi Layer Insert – MLI). It consists of multiple thin metal foils to distribute load optimally into every single CFRP layer. The placement process for the metal layers is integrated into an Automated Fiber Placement system. In this paper, a process sequence of MLI placement is presented containing the following steps: stockpiling of metal layers, separation, handling, positioning, lay up and fixation of metal layers during fiber placement. Moreover, the monitoring and control concept is discussed.

Peer-review under responsibility of the scientific committee of the 10th CIRP Conference on Intelligent Computation in Manufacturing Engineering

Keywords: Intrinsic Hybrid Compound; Automated Fiber Placement; Process Monitoring

1. Introduction

Nomenclature

AFP	Automated Fiber Placement
AIP	Automated Insert Placement
CNC	Computerized Numerical Control
CFRP	Carbon Fiber Reinforced Plastic
FRP	Fiber Reinforced Plastic
MLI	Multi-Layer Insert
Prepreg	Pre-impregnated fiber reinforced plastic

Thin walled FRP structures always face the issue of force application and transmission into the material. Within the program of emphasis 1712 “Intrinsic hybrid composites for light weight structures” different concepts for material hybridization are developed aiming at improved force transmission into light weight structures. The approach of the sub project “Multi-Layer-Inserts” deals with hybrid laminates, which will offer a higher potential to design a fiber-fair connection between a discrete attachment point and the laminate.

One of the main challenges, which the project is facing, comes with the need for a fully automated production process. The use of an advanced automated fiber placement process (AFP) in which an Automated Insert Placement (AIP) is integrated will ensure a reliable intrinsic hybridization and cost efficient production of such structures.

1.1. Concept of a Multi-Layer Insert

The project proposes a new type of insert built from multiple metal layers (Multilayer Insert, MLI), whereas the thickness of a single layer is equal to the corresponding FRP Layer. The metal inserts are coated with a thin film of structural adhesive to meet strength requirements and to counteract electrochemical corrosion when using aluminum as insert material. Even though there are only CFRP laminates

Peer-review under responsibility of the scientific committee of the 10th CIRP Conference on Intelligent Computation in Manufacturing Engineering
doi:10.1016/j.procir.2016.06.046

investigated in the following, this approach is generally applicable to every FRP material. Fig. 1 shows one example structure of a MLI integrated into a CFRP layup.

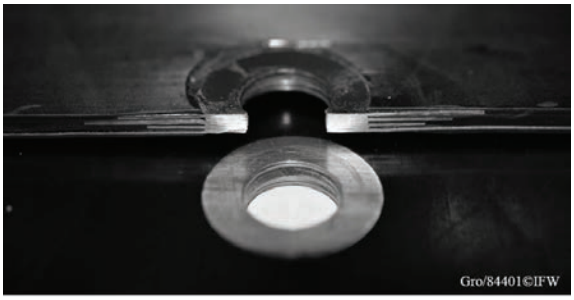

Fig.1. Multilayer Insert integrated into thin walled CFRP structure

Locally replacing CFRP by metal layer by layer, instead of using a relatively thick metallic component as an insert, leads to a reduced filament deflection and hence increases the laminate strength. The overall contact surface area between FRP and metal can be increased dramatically by means of using multiple metal layers instead of one single layer, which results in higher transmittable forces and a smaller insert with corresponding weight savings.

Two different types of metal layers are stacked to form the MLI. The larger one has the shape and size to transfer the load equally into the laminate, while its orientation matches the fiber orientation in the corresponding CFRP layer. Meanwhile, the smaller insert acts as a spacer between the larger ones, increasing the available surface for load distribution. An alternating stack of the two described metal inserts forms the MLI and creates an all metal area around the attachment point inside the CFRP laminate.

According to field of application, the project investigates different types of design for the attachment point itself, including conventional bolt or rivet connections as well as stud welding.

1.2. Weight saving and strength

First investigations with a manual manufactured laminate have been conducted to show the potential of the MLI compared to a conventional insert [1]. Fig. 2 shows exemplarily a result of a parallel pull out test carried out with a standard bigHead® insert, a stainless steel and an aluminum MLI integrated into a 2 mm virtually isotropic CFRP layup. The three tested insert types all use a M6 threaded bolt as attachment point.

With a stainless steel 1.4310 MLI the maximum load increases compared to the bigHead® insert, as can be seen in fig. 2. Concurrently, this insert is 41 % lighter compared to the bigHead® insert, which weighs about 9 g. With a MLI made of aluminum, there can even be spared about 80 % of weight, although with a decreased maximum load.

This investigation has been conducted without using the above mentioned structural adhesive, further investigations therefore are expected to show even better results.

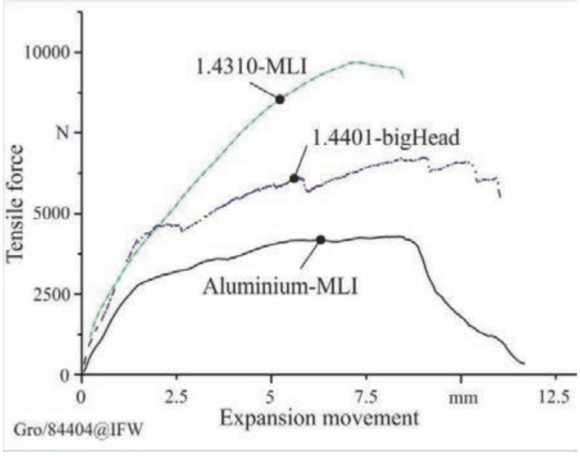

Fig.2. Comparison of different inserts and applicable forces

2. AIP Process

As aforementioned, the AIP module is integrated into an AFP laying head. An overview of the whole setup is shown in fig. 3, consisting of the AFP laying head, the AIP module, a laser line scanner and an infrared camera used for process monitoring.

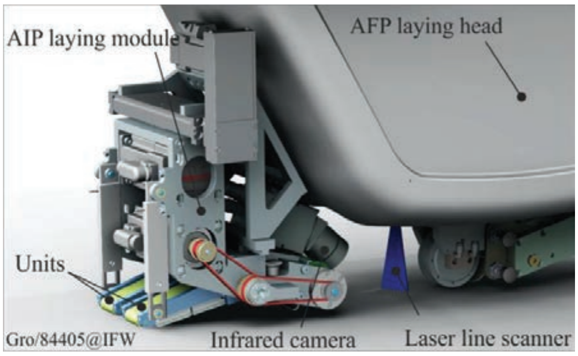

Fig.3. AFP laying head with integrated AIP module

2.1. AFP laying head

Within the interdisciplinary research project “HP CFK” [2,3], an AFP system has been developed, which provides the basis for insert placement in this project. The experimental laying head is capable of processing four 6.35 mm (¼”) prepreg slit tapes, which can be cut and handled individually. It is mounted to a KUKA 300 six-axis industrial robot, which is able to realize a process speed of up to 1 m/s. Furthermore, the setup provides a linear motor with a mounted tool plate, which can reach a laying speed of up to 3 m/s with a stationary laying head. Heating is realized through infrared radiators located ahead of the compaction roller.

2.2. AIP process chain

For every metal insert, an area in the CFRP layup need to be left out. Therefore, the AFP laying head generates a gap of defined length in the predefined location while building up the laminate. Downstream the compaction roller of the AFP laying head, the laser line scanner detects the contour of the generated gap. Data evaluation is performed online to control the MLI placement accordingly, see chap. 4. Subsequently, the AIP module supplies the metal insert with matching speed and pressure and places it in the desired spot.

In the course of the subsequent layer of laminate, the gap for the next MLI is created, while the infrared camera detects the position and orientation of the MLI placed beforehand, see fig. 4. This process repeats until the desired number of plies is palced, depending on the load to ransfer through the MLI and the thickness of the surrounding laminate.

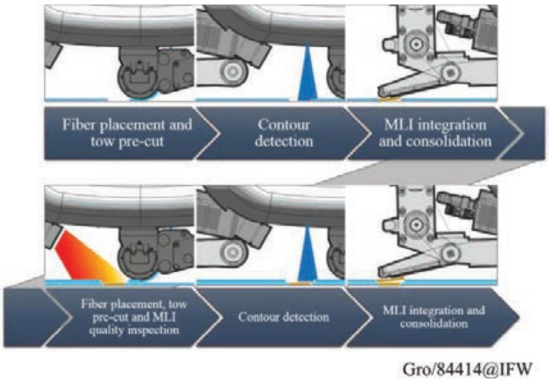

Fig.4. Process chain for AIP process

2.3. Optical measurement and inspection

During the standard AFP process, the infrared camera is used for online quality inspection, which is investigated in the research project “Therm-O-Plan” [3,4]. The camera measures surface temperature induced by the heat input of the radiators to detect defects and foreign objects during layup. As the MLI resembles a foreign object of disparate material on the layup, the infrared camera can easily detect and measure position and orientation of the insert, see fig. 5.

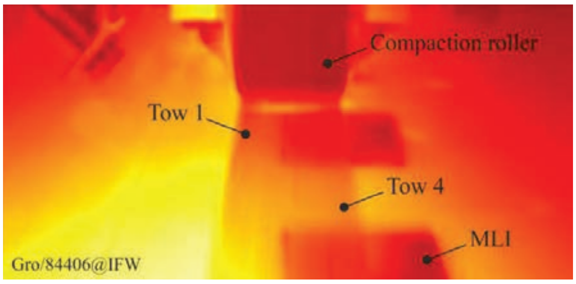

Fig.5. Infrared picture of Multilayer Insert partly abscured by CFRP

Tests have shown that those measurements can still be performed if one layer of CFRP obscures the MLI. While heating, the metal insert does not take as much thermal energy as the surrounding CFRP surface due to a lower absorption coefficient. As a secondary effect, the MLI is detectable through the temperature gradient in the following top layer of CFRP, see fig. 5.

The laser line scanner integrated in the setup measures the part surface to calculate the cutting edge and control the AIP process accordingly. Chap. 4 discusses the detection of cutting edges more closely. In the further course of the project, the laser line scanner can as well be used to detect different kinds of defects as discussed in [5,6] and realize online process monitoring in combination with the infrared camera.

3. Layup module

Due to the structure of the MLI described above, the AIP module is equipped with two individual units to handle two types of metal inserts with varying size and geometry. Every unit consists of a magazine to store metal inserts, a toothed belt drive to handle the inserts and a winder to reel the separation liner, see fig. 6.

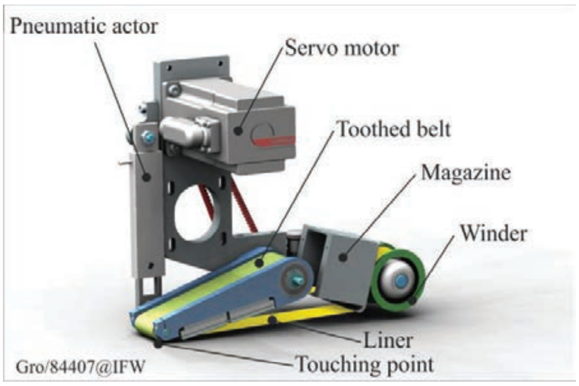

Fig.6. Single unit of AIP module

3.1. Insert size and geometry

Shape and size of the MLI used in industrial applications will vary considerably depending on the application purpose. The development of the AIP module in this project underlies a rectangular format of 26 x 45 mm for the larger metal insert. The width of 26 mm resembles the track width of the AFP laying head, while the length of 45 mm resembles the maximum feasible size in this design, which is restricted by the narrow building space underneath the infrared camera, see fig. 3. According to the structure of the MLI discussed in chap. 1, the smaller insert has a square format of 26 x 26 mm. A single metal layer has a thickness of 100 µm to match the dimensions of the prepreg material with a thickness of 125 µm. This leaves a residual 25 µm of space for structural adhesive and an optional protective coating. The latter one would mainly be applied when using aluminum as insert material, while this study uses stainless steel 1.4310.

As the AFP laying head cuts the prepreg tow orthogonally to the laying direction in its current development stage, it is only possible to choose a rectangular shape for the metal insert in this application purpose. Furthermore, the project considers divergent shapes such as elliptic ones.

3.2. Handling of inserts

On the one hand, adhesive between the single metal layers is needed to meet structural requirements. On the other hand, the adhesive poses some problems when it comes to handle the single metal inserts during automated placement. For this reason, the concept uses a separation liner between the single metal inserts to prevent them from adhering to each other during the handling process.

Regarding a single unit of the AIP module as shown in fig. 6 the magazine of this unit contains a stack of metal inserts, while the liner is placed in between them in a meandering zig-zag-pattern. This setup ensures a reliable separation of the metal inserts out of the magazine while facilitating the transport to the toothed belt at the same time.

A gap of defined width between the belt and a guide plate clamps the metal insert and prevents it from slipping relatively to the belt. The exposed structural adhesive on the upper side of the insert enhances adhesion to the belt, whereas the liner on the opposite side prevents it from sticking to the guide plate. A CNC controlled servomotor drives the belt to realize precise positioning and matching of AIP and AFP laying speed. Near the touching point between belt and part surface, the guide plate has a narrow radius at its end to peel off the separation liner from underneath the metal insert.

By using a toothed belt with a K1.5 profile, it is possible to realize a deflection radius of only 7 mm. This small radius enables a reliable withdrawal of the belt on the upper side of the insert without peeling it off from the CFRP part. The pneumatic actor supplies the appropriate force to consolidate the metal layer at the touching point.

A winder behind the magazine picks up the excess separation liner and at the same time maintains the tension needed to peel it off from the insert. For this purpose, an adjustable hysteresis brake running at slippage generates a momentum of max. 0.05 Nm.

3.3. Positioning of inserts

The AIP module is able to process two different geometries of inserts and therefore needs to be movable to select the appropriate unit, see fig. 3. Furthermore, the possibility to move the whole AIP module allows to choose the specific track tow 1 to tow 4 in the AFP layup in which to put the MLI. This facilitates to narrow the MLI placing pattern from 26 mm (four tow tracks, width of compaction roller) down to 6.5 mm (one track).

4. Laser line scanner

A Keyence laser line scanner LJV 7080 was integrated into the laying head for the contour detection. Table 1 gives a brief overview of its key specifications.

Table 1. Laser line scanner Keyence LJV 7080 [7]

Specifications	
Wavelength	405 nm (Blue laser)
Reference distance	80 mm
Measuring range (Height)	23 mm
Measuring range (Width)	32 mm (At reference distance)
Profile data interval (Width)	50 µm
Resolution (Width)	800 Pixel
Spot shape (Dimensions of laser line)	Approx. 48mm x 48 µm (At reference distance)
Sampling cycle	16 µs

The LJV 7080 is a compact sensor with a laser line projector and a camera integrated in a housing. It works using the triangulation principle with the camera looking at the projected laser line at a certain angle, see fig. 7 [8]. This way, a height profile can be acquired by evaluating the position of the line in the 2D image of the camera.

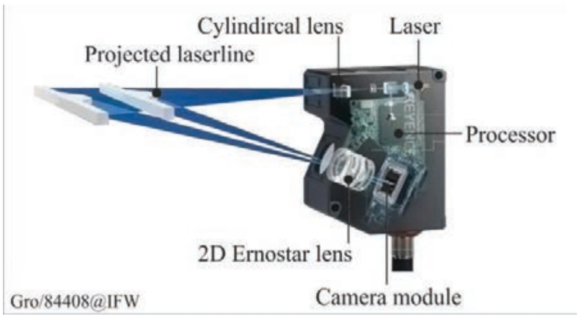

Fig.7. Keyence laser line scanner working principle based on [8]

4.1. Arrangement

To detect cutting edges during the AFP process, the laser line scanner needs to measure a difference in height of only 125 µm, as this is the thickness of one prepreg tow.

CFRP surfaces show some special characteristics, when it comes to optical measurement methodologies, that need to be considered.

- Low reflection coefficient

  A black CFRP surface absorbs most of the emitted light of the laser beam, which makes it difficult for the inbuilt camera to detect the laser line and perform the measurement reliably. One possibility to meet this problem could be to increase the exposure time of the camera, which, however, leads to a slower frame rate and therefore to poor dynamic behavior.

- Anisotropy
  Because CFRP, on a microscopic scale, consists of single fibers with a circular profile, it shows some anisotropic optical characteristics. If the laser beam is projected on the surface parallel to fiber orientation, part of the light is being reflected directly into the optics of the camera. When projecting the line orthogonally relative to the fiber orientation, only a small amount of the light is visible to the camera, as the majority gets reflected away from the optics due to the circular profile of the fibers.

However, the relative angel between laser line and fiber orientation does not only effect the optical detectability of the line itself, but in the present case also affects the achievable accuracy in detecting the cutting edge. As aforementioned, the used AFP laying head cuts the prepreg tow orthogonal to the laying direction in the current development stage. If the laser line has an orientation exactly parallel to this cutting edge, the achievable resolution is solely depending on the sample frame rate and the laying speed. For instance, if the laser line scanner works at a sample rate of 1 kHz, the samples have an interval of 1 mm at a laying speed of 1 m/s. Hence the resolution for detecting the cutting edge is geometrically limited to +/- 0.5 mm. In addition, this resolution is depending on the actual combination of laying speed and sample frequency, which may vary throughout the process. In this scenario, the high 50-µm-resolution of the laser line scanner remains unused. Moreover, the detection gets unreliable, as the criterion for detecting the edge is not a discrete step within one sample but rather a difference of 125 µm in the height level between two samples, see fig. 8. Due to vibrations induced by the laying process and other disturbances, this relatively small value falls in the range of noise when travelling at such laying speeds.

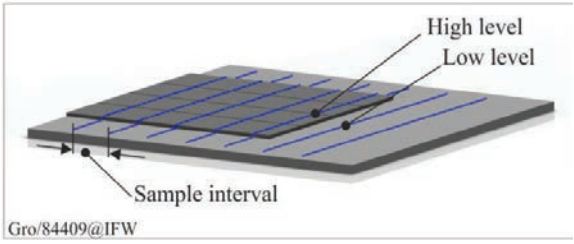

Fig.8. Measurement at 0° working angle

For this reason, tests have been conducted using a working angle of 30° between the laser line and the Y-axis of the laying head, see fig. 9.

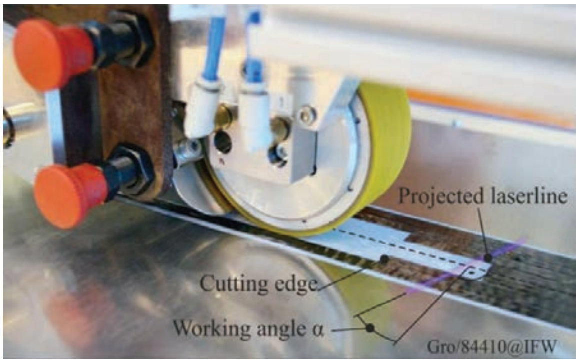

Fig.9. Projected laserline with 30° working angle

With this specific setup, the cutting edge is detectable as a drop in the profile of one sample, see fig. 10/12. Therefore, the geometrical resolution can be increased to:

$$res_{total} = \frac{res_{scanner}}{\cos(\alpha)} = 100\,\mu m \qquad (1)$$

With this setup, the resolution is depending on the specifications of the laser line scanner itself and therefore remains constant throughout the process. As a secondary effect, the edge is detectable in 12 consecutive samples regarding the above-described boundary conditions, which leads to a more stable and reliable measurement to control the process.

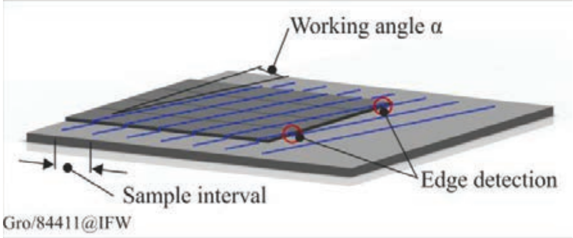

Fig.10. Measurement at 30° working angle

4.2. Measurement results

Fig. 11 shows the surface plot of a measurement sample taken during the AFP process. The data has been recorded at a laying speed of 0.3 m/s and a frame rate of 1 kHz.

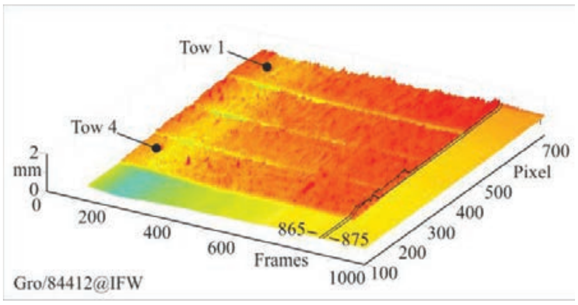

Fig.11. Laser line scanner surface plot showing the cutting edge of 4 tows

The plot shows four 6.35 mm prepreg tows with a pictured length of 250 mm, while the tool surface underneath is build up from an aluminum plate covered with vacuum foil.

With the above described setup, the edge can be detected as a drop in several profiles taken in the corresponding area. Fig. 12 shows the profile of samples 865 and 875 with clearly visible edges, while the position of the drop changes its locatioin from frame to frame. This way, the position of recognized drop can be calculated in every frame according to the above described geometrical relation. Interpolation between those positions in different frames finally results in a stable and robust calculation of the position of the cutting edge and the contour where to place the MLI.

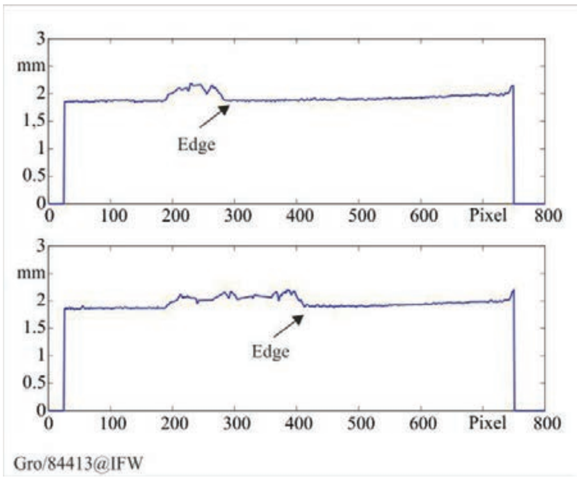

Fig.12. Profiles 865 and 875 in area of cutting edge

5. Summary and outlook

This paper introduces a new hybrid insert for thin walled FRP structures consisting of multiple metal layers, the MLI. A concept for automating the layup of such an insert is presented and discussed with focus on optical measurements for means of online controlling and process monitoring. A laser line scanner meets the requirements to perform reliable detection of the cutting edge at high laying speeds of up to 1 m/s.

The AIP module presented in this paper is currently under construction, tests to determine the dynamic performance of the setup will be performed subsequently. Meanwhile, structural tests with differing geometries and setups will validate the potential of the new insert type.

Acknowledgements

The authors would like to thank the German Research Foundation (DFG) for funding the research work “Multi-Layer-Inserts” as part of the program of emphasis 1712 “Intrinsische Hybridverbunde für Leichtbaustrukturen” (“Intrinsic hybrid composites for light weight structures”). They also thank the federal state of Lower Saxony and the European Regional Development Fund (ERDF) for funding the preceding project “HP CFK”.

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