PAPER • OPEN ACCESS

Vision based quality control of composite components: considerations about measurement accuracy

To cite this article: Giulio D'Emilia *et al* 2021 *J. Phys.: Conf. Ser.* **1977** 012005

Journal of Physics: Conference Series **1977** (2021) 012005 doi:10.1088/1742-6596/1977/1/012005

Vision based quality control of composite components: considerations about measurement accuracy

Giulio D'Emilia[1]*, Antonella Gaspari[2], Emanuela Natale[1] and Davide Ubaldi[1]

[1]Department of Industrial and Information Engineering and Economics, University of L'Aquila, Italy

[2]Department of Mechanics, Mathematics and Management, Polytechnic of Bari, Italy

*giulio.demilia@univaq.it

Abstract. In this paper a methodology is discussed concerning the measurement of yarn's angle of a reinforced polypropylene matrix used in the production of automotive components. The measurement method is based on a vision system and advanced processing of images in order to evaluate the geometrical parameters of interest; the accuracy of measurement is a mandatory requirement, in order to assess the simulation approach for thermoplastic process optimization. Many aspects influencing the whole accuracy of the method have been identified and their effect evaluated, of both geometrical and optical type, allowing to perform angle measurements of the fiber angle with a whole accuracy in the order of a few degrees. By this way both local and extended defects can be identified in a reliable way also with reference to components of complex geometry. According to these results, accurate measurements of angle allows us to both validate the simulation of the thermoplastic process and to give suggestions for process improvement of fiber glass components of complex geometry.

1. Introduction

During the last decades, the use of advanced composites, in particular fiber reinforced plastic materials, has become more and more popular in a wide range of domains of activity, in particular in automotive and aerospace industries, due to their important characteristics, such as high strength-to-weight ratio, high stiffness-to-weight ratio, low density, wear resistance, chemical environment stability and long fatigue life, recyclability and their interesting capacity to be formed and produced in high volume rate [1].

Of great interest are the structural characteristics of the material, which influence the mechanical characteristics of the produced composite parts. In fact, fiber reinforced plastic materials, consisting of a polymer matrix reinforced by fibers, exhibit an orthotropic behavior due to fibers orientation. For this reason, it is crucial to consider the fibers orientation as a major factor in the entire technological process, starting from the design and finishing with components cutting [2, 3].

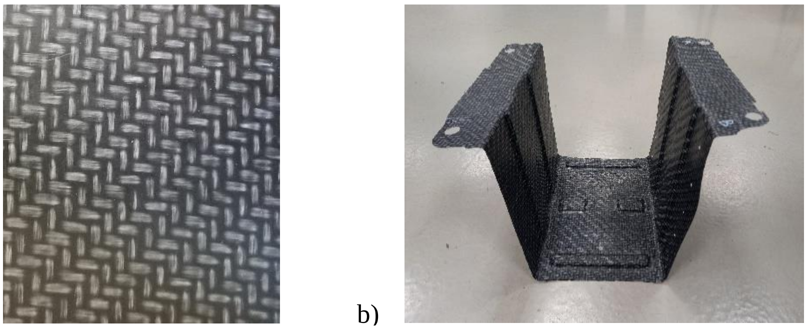
The fiber misalignment is a dominant defect of the tensile and compressive properties of these materials [4].

The textile draping process is one of the most critical steps in the production of fiber reinforced thermoplastic composite, from this point of view. In fact, in the draping process a flat textile has to be

adapted to a 3D geometry, and this induces shear deformations and changes the local yarn orientation, which can be critical to the performance of the material [3].
These phenomena are usually being addressed experimentally by performing large deformation mechanical tests such as the bias-extension and the rotational bending which are complicated and conducted in the temperatures of reference in which each material can be thermoformed. Usually, the output of these tests is the basis of a process simulation using Finite Element (FE) modelling as indicated in [5-7].
Simulation plays a fundamental role as for process optimization, even though many aspects should be taken into account, with reference to both physical and chemical characteristics of materials and real operating condition during the production process [8-10], and integration with experimental evaluations is an unavoidable aspect of the approaches aiming at the optimization of the production process.
To set up a simple validation system for the experimental assessment of the FE process, requirements concerning accuracy of measurements should be satisfied, in order to guarantee an effective interaction between simulation and experiments [11-13]. This goal is not simple, considering the many aspects interfering with measurements, which are multiple and of different type, related to the procedure, to the measurement system, to the material characteristics, only to cite the main ones.
Different methods are proposed in literature for the measurement of yarn orientation in draped fabrics.
Some methods measure the yarn orientation directly from digital images of the draped fabric by the use of image analysis algorithms such as edge detection or gradient methods [4, 14]. These direct optical methods are useful for one-layer fabrics, or to inspect only the uppermost layer in multi-layer materials.
A different method is based on the analysis of the bi-directional reflectance distribution function (BRDF) [15], which determines the yarn orientation by using the direction-dependent light reflection characteristics of the carbon and glass fibers. Image analysis is based on photometric stereo and uses different illumination patterns in combination with a fiber reflection model.
The restriction of the analysis to the uppermost layer can be overcome by using electrical inspection methods. High-frequency eddy current testing is often used for the detection of fabric defects such as gaps and foreign materials [16-18], but it can be also used to visualize yarns in fabrics, inducing a circular eddy current in the specimen and measuring the resulting electromagnetic field effects [3]. For this method, the fibers of the composite material have to be conductive, which is the case for carbon fiber fabrics, but not, for example, for glass fiber composites.
An interesting and promising line of research concerns the analysis of images acquired with polarized cameras. It is known, in fact, that the fiber strands influence the incident light and mainly reflect light of a certain polarization orientation. With a simple unpolarized illumination, the polarization of the reflected light can be measured and directly gives the orientation of the fibers, for the uppermost layer of fibers, even with resin being applied [19].
A variety of polarization sensors have been developed in the last years, among which camera-based polarization sensors, which can measure multiple direction information of polarization pattern [20, 21] and which can be very useful in studying the deformations of the uppermost layer of fibers of composite materials.
One important point that appears in research works where a comparison is made with simulation, is that a deviation of 10° or more between predicted and measured fiber or shear angles is generally found [3, 5, 22], then further research on both simulation and measurement methods is of current interest.
In this paper a contribution to the set-up and optimization of the fabrication process of glass fiber thermoplastic composites is provided, by means of fiber angles measurements, carried out with more types of processing techniques of the acquired images.
The methods will be critically evaluated and compared, to be used, in the future work, to validate simulation results. Indications from the uncertainty evaluation will allow to optimize the experimental set-up and the procedure in order to obtain the validation and the assessment of the simulation results at a suitable level of uncertainty for an effective control of the production process of parts made of thermoplastic composite material.

2. Materials and methods

The material under analysis consists of a polypropylene matrix reinforced with a woven 2-2 twill E-glass textile (figure 1.a). The fiber volumetric content is 47%, while the melting point of the material in total is 163 °C. Nevertheless, the temperature's window opens approximately at 130 °C.
Measurements have been carried out first on reference image (drawing made with a CAD software), to evaluate the accuracy of the methods, and then on a flat piece of the composite material analyzed, to evaluate the variability of the yarn angles on the planar starting plate.
In the next phase, measurements have been carried out on a 3D object, obtained by thermoforming process, that is a component destined to support the battery tray of a car (figure 1.b), a fact which signifies the importance of its integrity while in service [11]. To this end, extreme fiber deformation and variation of the thickness of the component may lead to undesired structural instability.
A FLIR Camera, 2448x2048 pixels, has been used for the acquisition of the images. As far illumination, two soft-boxes with 80W lamp bulbs are used.



a) b)

Figure 1. a) Planar surface of the composite material. b) 3D object analyzed.

In the next phase, measurements have been carried out on a 3D object, obtained by thermoforming process

2.1 Yarns angle measurement methods

The images are digitally post-processed in order to measure the angle between fibers; the processing is carried out by means of a specific, high performance software for geometrical analysis of elements in pictures, the Vision Builder for Automated Inspection, by National Instruments.
Among the functions available in the Vision Builder software, those for edge detection are useful in the specific application. To locate an edge, a search direction has to be set (figure 2.a), along which the intensity differences between pixels are detected. Figure 2.b provides a graphical representation of the edge contrast along the search line. Edges are identified by peaks in the edge strength profile. A minimum edge strength is also defined, which specifies the minimum required difference between the intensity values of the edge and surrounding pixels (the blue lines in figure 2.b).
To find the whole edge line, a region of interest (ROI) has to be defined, in which a certain number of research lines (whose distance can be set) are distributed (figure 3). A fitting of the identified points provides the searched edge.

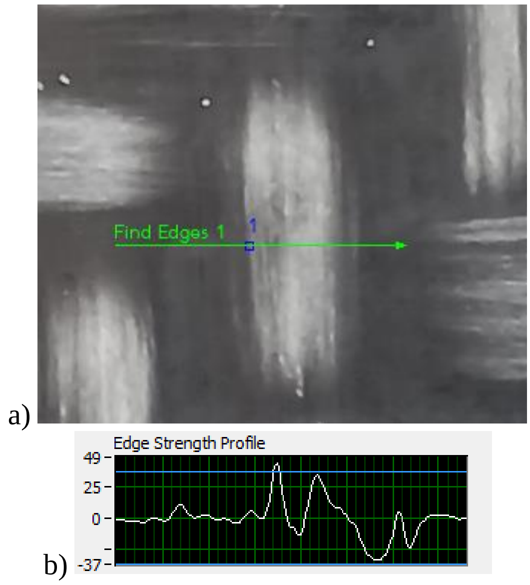


Figure 2. a) Search line for edge identification; b) edge strength profile along the search line.

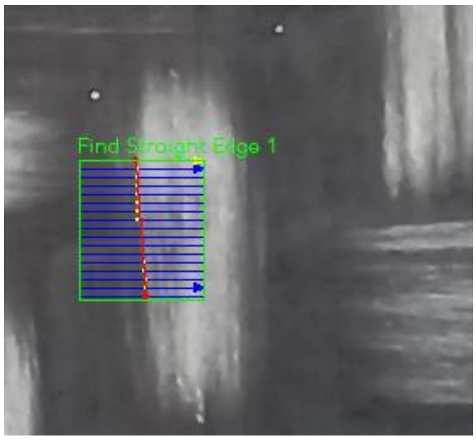


Figure 3. ROI for edge identification.

Two different strategies of inspection of the composite surface are analyzed:

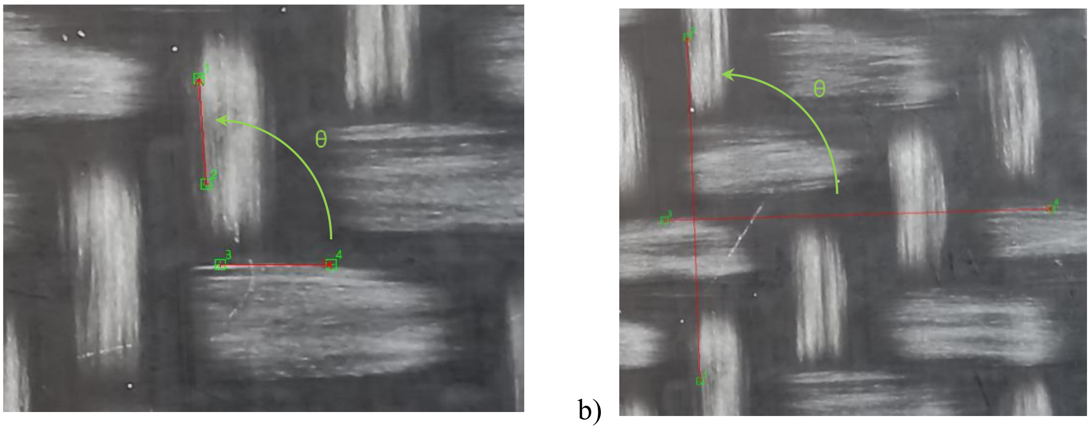
- The first (Method 1) involves the identification of the straight edge of the individual glass yarn elements (figure 4.a). Pairs of adjacent elements are selected for determining the angle θ between fibers.
- The second (Method 2) involves the determination of two edge points on two consecutive glass yarn elements in the vertical direction, and the same is made for the horizontal one (figure 4.b). In this way the angle measurement is made using more spaced points, which is an advantage from the point of view of the accuracy of the angle measurement. However, in this way, strongly localized effects, if any, are attenuated.

After a preliminary validation of both methods on a reference twill fabric picture, the following plan of the experiments has been carried out:

a. Measurements on a flat plate whose nominal angles are 90°:
    - 32 repeated measurements, realized with reference to the same couple of yarns.
    - 32 measurements on different couples of yarns, taken on an area of 200x200 mm^2.

- 96 measurements distributed on a plate of 1000x310 mm^2.

b. Measurement on a 3D object (figure 1.b).



a) b)

Figure 4. The two different inspection strategies taken into account: a) Method 1; b) Method 2.

3. Results

3.1 Measurements on the flat plate

The preliminary validation with respect to a reference image, where all the angles are 90°, provided satisfactory results, being the variability of repeated measurements in the order of hundredths of a degree, and the average value of the angle centred on the reference value of 90 °.
The results of the tests carried out on the flat plate are summarized in figure 5 and figure 6.
Figure 5 shows the histogram of the results obtained with reference to the same couple of yarns, together with the histogram of the results of measurements, carried out on different couples of yarns, on an area of 200x200 mm^2. In particular, figure 5.a refers to the results of Method 1, while figure 5.b refers to the results of Method 2.
About Method 1, the distribution has mean and standard deviation of 91.9° and 3.2°, respectively, when the same couple of yarns is considered in repeated measurements, and average angle of 93.2° and standard deviation of 4.4° when different couples are considered.
About Method 2, the distribution has mean and standard deviation of 90.8° and 0.67° when the same couple of yarn is considered, and average angle of 91.2° and standard deviation of 3.2° when different couples are considered.
Then, as would be expected, Method 2, which uses more spaced points for the measurement, presents a lower variability than Method 1.
It can also be observed that the variability evaluated on the same pair of yarns takes into account the variability of the methods, which are affected by the way in which the regions of interest or the points used for the measurement are selected.
Instead, the variability evaluated on different couples of yarns is also affected by the variability of the measurand, that is the superficial inhomogeneity typical of the analysed material; a rough estimate of the angle variability, based on the above results of both methods is in the order of 2-3 °.
It must be observed that Method 2, although characterized by less variability, is less suitable for measuring angles on non-flat surfaces, where the deformation of the texture can undergo rapid variations passing from one point to another on the surface, because in these cases a more punctual measurement is required.
For this reason, Method 1 has been chosen for the measurements on the 3D part. To more accurately determine the overall variability for Method 1, which integrates the contributions due to the method and

to the variability of the measurand, 96 measurements have made on a 1000x310 mm^2 plate. The results are represented in the histogram of figure 6. The distribution has mean and standard deviation of 91.1° and 2.0°, respectively.

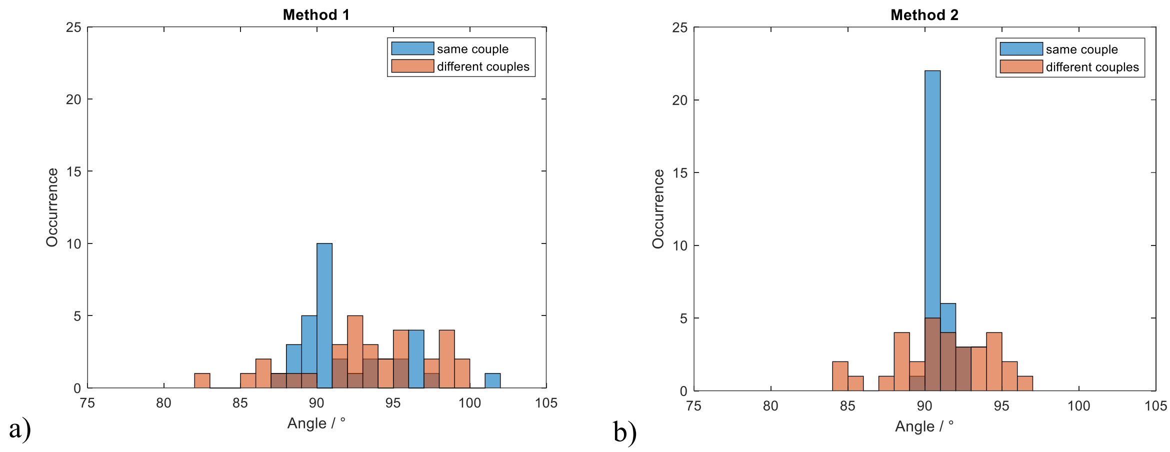


Figure 5. Distribution of measurements on the same couple of yarn and on different couples of yarns on an area of 200x200 mm^2, using: a) Method 1, b) Method 2.

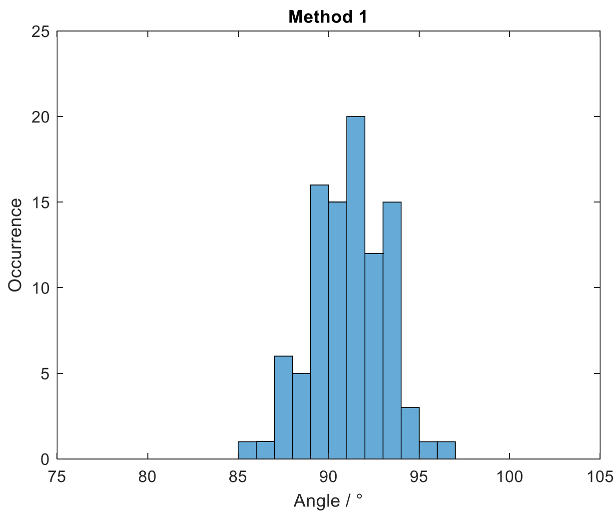


Figure 6. Distribution of measurements made by Method 1, on a 1000x310 mm^2 plate.

3.2 Measurements on the 3D object

Measurements have been carried out on the 3D object, shown in figure 1.b, obtained by a thermoforming process. The component was obtained starting from a flat sheet which, during thermoforming, undergoes deformations in the fabric due to the friction between sheet and mold. These deformations produce a concavity of the horizontal fibres, facing up or down in specific areas of the component, called zone A and zone B, respectively (figure 7). These defects are favoured by the fact that the matrix is made viscous by the high temperature of the furnace before forming, which allows a freedom of movement to the fibres, thus facilitating the deformation of the fibres themselves.

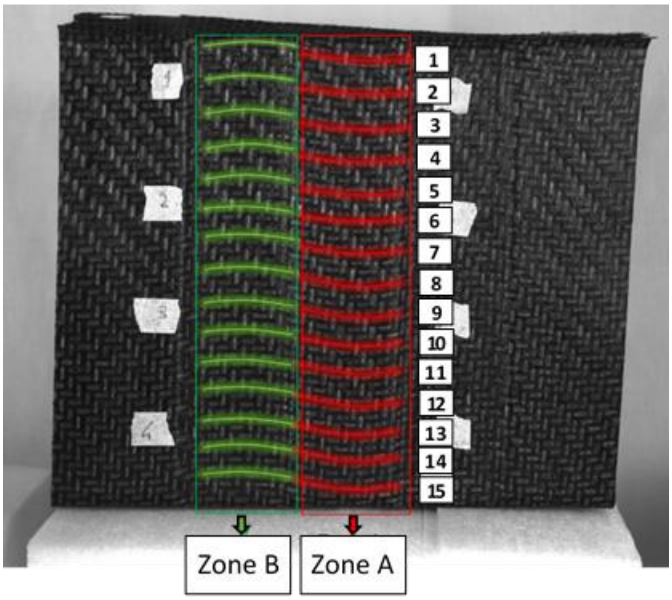


Figure 7. Zone A and B on the lateral face of the object, and lines of measuring.

To evaluate this effect, a reference system has been set, with y-axis in the direction of the lateral vertical fibres, and the α angle between the fibres and the x-axis (figure 8) has been measured in correspondence with 15 lines over the entire height of the lateral part of the object (figure 7). The aim is to define a reference system integral with the piece, independent of its orientation within the image. The definition of a reference system is not trivial and it influences in a remarkable way the whole uncertainty of the measured angles.

Considering the zone A, in which the fibres have concavity upwards, it is clear that there must be angles close to zero in the central part of the zone, angles less than zero on the left side, and greater than zero on the right side (figure 8).

For zone B, the trend is opposite, i.e. α is greater than zero on the left, equal to zero in the centre, and less than zero on the right.

These theoretical observations are confirmed by the experimental results, which are represented as a heat-map in figure 9.

These measurements can be useful information for the optimization of the process, since the simulation alone cannot easily predict these effects of localized deformation of the texture. Furthermore, resolution and uncertainty of results are low enough to suggest process modifications and improvements, in order to reduce unwanted grid distortions.

4. Conclusions

A methodology for the measurement of the yarn angle of a composite material of glass fibre has been discussed, based on a vision system and an advanced image processing procedure for process simulation validation.

The method has proved to be able to identify local behaviour of fibre but also to describe surface trends of angle between fibres, where the acknowledgement of reduced variations of fibre orientation is able to suggest improvements to the thermoplastic process.

This ability has been reached thanks to the satisfactory uncertainty of angle measurements based on image processing.

The assessment of uncertainty required to identify the main aspects influencing uncertainty and to evaluate their contribution.

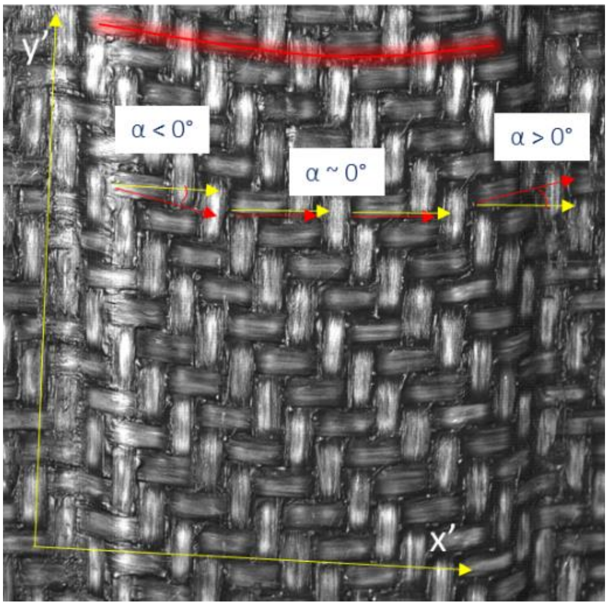


Figure 8. Reference system and definition of the α angle

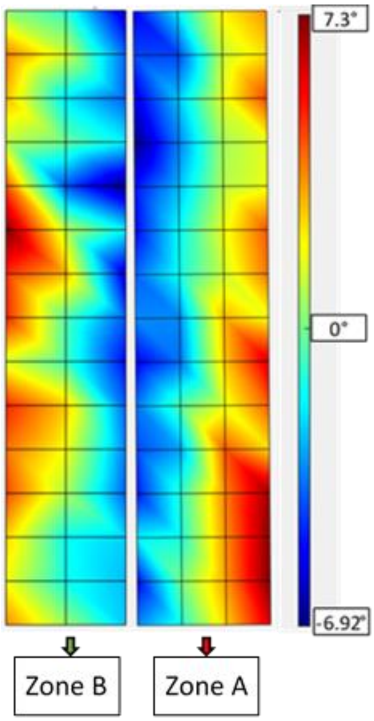


Figure 9. Heat-map of the measured angles, on Zone A and B.

In particular, the main aspects to be considered are both geometrical and optical, like area of interest, yarn fibre boundary identification, camera resolution, lighting conditions and, in case of three-dimensional objects and defects, also the local reference system. Calibration of the whole measurement system, with reference to this specific surface, is also of concern.

Angle measurement uncertainty in the order of a few degrees allowed us to describe the studied defects in a satisfactory way; the future work will be devoted to check the reproducibility of procedure in different applications, also with very challenging geometries.

5. References

[1] Di Ilio A, Di Genova L G and Stamopoulos A G 2021 Implementation of the modified V-Notched Rail Shear method for characterizing glass fibre thermoplastic composites at sub-zero and elevated temperatures *Polym. Test.* **93** 106174

[2] Bardl G *et al* 2018 Analysis of the 3D draping behavior of carbon fiber non-crimp fabrics with eddy current technique *Compos. Part B-Eng.* **132** 49-60

[3] Şerban A 2016 Automatic detection of fiber orientation on CF/PPS composite materials with 5-harness satin weave *Fiber. Polym.* **17** 1925-33

[4] Zheng T, Guo L, Shun R, Li Z and Zhu H 2021 Investigation on the compressive damage mechanisms of 3D woven composites considering stochastic fiber initial misalignment *Compos. Part A-Appl. S.* **143** 106295

[5] Di Ilio A, Stamopoulos AG 2019 On the predictive tools for assessing the effect of manufacturing defects on the mechanical properties of composite materials *Procedia CIRP* **79** 563-7

[6] Stamopoulos A and Di Ilio A 2021 Numerical and experimental analysis of the thermoforming process parameters of semi-spherical glass fibre thermoplastic parts *Procedia CIRP* **99** 420-5

[7] Haanappel S P, Ten Thije R H W, Sachs U, Rietman B and Akkerman R 2014 Formability analyses of uni-directional and textile reinforced thermoplastics *Compos. Part A-Appl. S.* **56** 80-92

[8] Zhang H, Chen J and Yang D 2021 Fibre misalignment and breakage in 3D printing of continuous carbon fibre reinforced thermoplastic composites *Additive Manufacturing* **38** 10177

[9] Duboust N, Watson M, Marshall M, O'Donnel G.E and Kerrigan K. 2020 Towards intelligent CFRP composite machining: surface analysis methods and statistical data analysis of machined fibre laminate surfaces *P. I. Mech. Eng. B-J. Eng.* 0954405420960920

[10] Semlali AouraghHassani FZ, El Achaby M, Bensalah MO, Rodrigue D, Boufidh R and Qaiss A E K 2020 Injection molding of short fiber thermoplastic bio-composites: prediction of the fiber orientation *J. Compos. Mater.* **54** 4787-97

[11] Stamopoulos A G, Spitilli P, D'Emilia G, Gaspari A, Natale E and Di Ilio A 2020 Assessment of the measurements contribution on composites thermoforming processes: a case study of an automotive component *2020 IEEE Int. Workshop on Metrology for Industry 4.0 and IoT, MetroInd 4.0 and IoT 2020 – Proc.* pp 299–303 9138197

[12] D'Emilia G, Di Ilio A, Gaspari A, Natale E, Perilli R and Stamopoulos A G 2019 The role of measurement and simulation in additive manufacturing within the frame of Industry 4.0 *2019 IEEE Int. Workshop on Metrology for Industry 4.0 and IoT, MetroInd 4.0 and IoT 2019 – Proc.* pp 382–7 8792876

[13] D'Emilia G, Di Ilio A, Gaspari A, Natale E and Stamopoulos A G 2020 Uncertainty assessment for measurement and simulation in selective laser melting: a case study of an aerospace part *ACTA IMEKO* **9** 96-105

[14] Margossian A, Bel S, Balvers J M, Leutz D, Freitas R and Hinterhoelzl R 2014 Finite element forming simulation of locally stitched non-crimp fabrics *Compos. Part A-Appl. S.* **61** 152-62

[15] Zambal S, Palfinger W, Stöger M and Eitzinger C 2015 Accurate fibre orientation measurement for carbon fibre surfaces *Pattern Recognition* **48** 3324-32

[16] Heuer H, Schulze M and Pooch M 2016 High resolution radio frequency inspection of carbon fiber composites *21st Int. Conf. on Microwave, Radar and Wireless Communications (MIKON) IEEE* pp 1-4

[17] Mizukami K, Mizutani Y, Todoroki A and Suzuki Y 2016 Detection of in-plane and out-of-plane fiber waviness in unidirectional carbon fiber reinforced composites using eddy current testing *Compos. Part B-Eng.* **86** 84-94

[18] Mizukami K, Mizutani Y, Kimura K, Sato A, Todoroki A, Suzuki Y and Nakamura Y 2016 Visualization and size estimation of fiber waviness in multidirectional CFRP laminates using eddy current imaging *Compos. Part A-Appl. S.* **90** 261-70

[19] Schöberl M, Kasnakli K and Nowak A 2016 Measuring strand orientation in carbon fiber reinforced plastics (CFRP) with polarization *19th World Conf. on Non-Destructive Testing*

[20] Ren H, Yang J, Liu X, Huang P and Guo L 2020 Sensor modeling and calibration method based on extinction ratio error for camera-based polarization navigation sensor *Sensors* **20** 3779

[21] Ahsan M, Cai Y and Zhang W 2020 Information extraction of bionic camera-based polarization navigation patterns under noisy weather conditions *Journal of Shanghai Jiaotong University (Science)* **25** 18-26

[22] Kärger L, Bernath A, Fritz F, Galkin S, Magagnato D, Oeckerath A, Schön A and Henning F 2015 Development and validation of a CAE chain for unidirectional fibre reinforced composite components *Compos. Struct.* **132** 350-8