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New concepts for quality assurance of lightweight material

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Abstract

Lightweight material became more and more important during the last years. To ensure a defect-free production, effective measurement solutions for quality assurance are necessary. The Laser stripe sensors enable the evaluation of form deviations. For the detection of internal defects thermography provides a suitable solution. On this account the combination of these two non-destructive testing principles gives an opportunity to detect different kinds of defects regarding the outer geometry and the material within the parts. This paper deals with varied concepts to combine laser stripe sensor system and thermography and shows the potential of these methods.

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Keywords: Sheet Moulding Compound; Laser stripe sensors system; Thermography, multi-sensor measuring machine

1. Introduction

Fiber-reinforced plastics are a high-performance material, which is used especially in automotive and aerospace industries [1]. For the planned reduction of fleet consumption to 95 g CO2/km, the automobile industry is forced to act [2]. Fiber-reinforced plastics, therefore, present a great potential for the weight reduction and fuel saving. However, the mechanical properties of glass fiber-reinforced plastics compared to metals are very low so that fiber-reinforced plastics can only be used to a limited extent for structural components. For structural components carbon fiber-reinforced plastic is used but the price of this material is high.

In order to compensate for this drawback, discontinuous fiber-reinforced plastics can be combined with continuously reinforced plastics, which are reinforced in the direction of flow of the force and thus improve the mechanical properties.

Sheet Molding Compound (SMC) provides a good basis for this. SMC belongs to the group of glass fiber reinforced duromers and is applied to many components on the automobile, such as spoilers or underlays [3]. The material is available as a pre-impregnated semi-finished product and, therefore, has advantages in terms of cycle time and productivity.

The reinforcement takes place with continuous carbon fiber-reinforced plastics (CFRP). These have high costs with respect to the raw material. For this reason, it is necessary to ensure the quality of the semi-finished products and, thus, of the final component at an early stage of the process chain. The challenge is that the final part is not composed of a homogeneous material but of a large number of components such as the matrix system or the reinforcing fiber [1].

In the combined process chain, a large number of errors can occur. This includes defects which are located on the surface of the components, such as shape and contour deflections, as well as internal defects such as delamination or air inclusions. In order to be able to examine the semi-finished product, it is necessary to use non-contact measurement technology. The various defects cannot be detected by a single sensor system. The laser stripe sensors method is suitable for the investigation of the outer shape deviations of the part [4]. Non-destructive testing (NDT), such as active thermography, have been shown to be promising for internal defects [5-6]. Moreover, ultrasonic-testing with air coupling can be a possible method [7], but it has been shown to be unsuitable for this application [8].

Thus, in order to be able to carry out a holistic quality assurance, it is necessary to combine several methods.

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Different measuring systems are discussed and evaluated in the following for their application with regard to the material combination and the fusion of different measuring systems.

2. State of the Art

2.1. Laser stripe sensors system

A laser stripe sensor system is an optoelectronic distance measuring instrument based on geometric relations from camera to laser and to the detected objects (triangulation principle). Therefore, a laser-generator irradiates the object and a camera detects the reflected laser beams. Being aware of geometric system configuration, the distance, particularly the surface distance elongation can be calculated. With a single laser stripe, a high-elongation of one surface stripe can be detected – which means detecting a single relief stripe [4]. To get a three-dimensional relief of the whole component surface, the system has to move along the surface. After scanning, the single stripes can be stringed together and represent the 3D image of the object's surface [9]. The combined picture of a calibrated system is called 'Cloud of points' (COP). This COP can also be converted to a 2.5-dimensional picture (the high-information is represented by the pixel's colours), so-called ZMap.

Depending on the geometry of the detected object (and its surface) there are some possibilities for a poor quality of COP: On the one hand, the camera's field depth is restricted, which means, that there is a small optimal distance range between the object's surface and the camera. For this reason, the system has to move over the relief in exact the same distance while scanning the surface. Another reason for a poor quality could be a shadow-effect of a single laser stripe sensor system: This problem could be solved by using two systems, which is shown in figure 1. For a shadow-effect parallel to the scanning direction, the systems could be twisted crosswise to the scanning direction [4]. Utilizing (detecting) highly reflecting materials or unfavourable geometries (e.g. special types of corners or edges) could result in useless reflection and so in a poor quality of COP. This effect is highly influenced by the laser-intensity and the system's triangulation-angle [11].

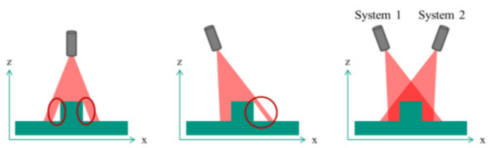

Fig 1. Laser stripe sensors and shadowing effects [7]

Previous experiments have shown that the most influencing parameters for scanning CFRP-components are: The laser-intensity, the integration time (camera), the threshold (lower intensity-minimum, which is needed to set a pixel as detected), the triangulation angle and the arrangement of a camera to laser [10]. The laser-intensity is determined by the voltage of the laser power supply. The camera's integration time is the time range, how long a pixel is influenced by the rays for one picture.

2.2. Thermography

Numerous studies have already shown that thermography is a NDT method which can be used to detect impact damage or fiber breakage well [11-13].

Thermography can be divided into active and passive thermography. In passive thermography, temperature differences caused by upstream processes are visualized [14]. In this way, for example, the temperature of the surface of components can be monitored. In the case of active thermography, the object is stimulated to electromagnetic radiation by thermal energy. In this way defects due to inhomogeneous temperature distributions can be determined [15].

The excitation can take place in different ways. Pulsed-phase thermography is available for a fast analysis which, compared to other methods, has increased sensitivity to errors [16]. This requires a flash lamp, as well as a thermal imaging camera. Using the Fast Fourier Transformation further evaluations can be carried out and thus more information can be obtained in comparison to the pure temperature curve.

2.3. Multi-sensor measuring machine

No non-destructive method is currently able to check a component holistically for all possible defects and faults. Each individual method has its own focus in order to check certain features and also has different resolution [16].

Through the use of different sources of information, it is possible to generate new knowledge, which has a higher degree of detailing and is often made available in a shorter time and at a lower cost [17].

In order to check components of discontinuous and continuous fiber-reinforced plastics for internal defects and geometrical deviations, it is advantageous to use several sensor systems and to fuse the results of the individual measurements.

3. Material

For the conduction of test measurements different sample geometries are used. For the thermography experiments, flat specimen with a thickness of up to 4.7 mm and a maximum size of 400 x 250 mm^2 are used. In experiments with the laser stripe sensors system, a hat profile is examined. Both sample geometries are shown in figure 2. All samples consist of the same material. The discontinuous glass fiber SMC consists of a vinyl ester resin (DSM) with 23 vol.% glass fiber content. A fiber volume of up to 50% is achieved for the continuous fiber material, which is a hybrid resin (DSM). The Continuous and discontinuous material is bonded to each other.

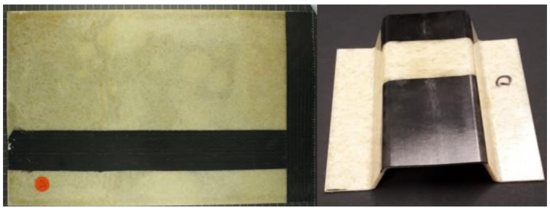

Fig 2. Sample geometries

All specimen are produced in the conventional SMC manufacturing process. Detailed information on the manufacturing process can be found in [18].

4. Experiments with laser stripe sensor system

4.1. Test execution

To ensure, a reliable detection of the contour of the testes material and a correct measurement alignment, the parameter settings of the laser stripe sensor systems have to be evaluated especially for SMC (semi-finished and cured SMC) and particularly for hybrid unidirectional SMC structures.

The test execution contains a 4-axes portal machine with two industrial cameras and two lasers. The camera detector is a CMOS sensor with a resolution of 2048*2048 pixels. With this amount of pixels, the theoretical resolution (in x-direction) is about 63 µm per pixel. The resolution for the z-axis is 138 µm/pixels (for a laser angle of about 3°) and 340 µm/pixels (20° laser angel). The ideal working distance to the surface of the object is 250 mm. Each camera-laser system is twisted with 5° (according to figure 1). The camera-laser arrangement matches with the so-called "look-away" geometry (figure 3).

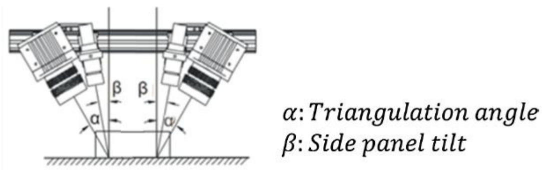

Fig 3. Camera-laser arrangement [19]

To prevent crosswise influences (due to combined scanning) the two systems are alternately working every 50 µm (which is also the approximate resolution for the y-axis) with a length of the laser line of 130 mm [16].

For creating realistic experimental conditions, two types of test geometry were designed and used: One geometry for cured SMC with continuous carbon fibers and one for semi-finished material. In detail, to ensure realistic conditions, the test pieces contain special elements, like corners or curves. Figure 4 shows the technical drawings of the test pieces.

Previous tests with SMC have shown, that the electric parameters (laser-intensity, integration time, threshold) despite the triangulation angle (figure 3: angle α) are the most influencing parameters for the quality of the COP. For that reason, only these parameters are varied during the

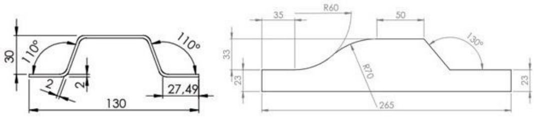

Fig 4. Left: Geometry for cured SMC (GEO-A);
Right: Geometry for wrought material (GEO-B)

experiments. The following plan shows which parameter values were tested:

			GEO-A									GEO-B								
			Integration time [µs]									Integration time [µs]								
			600			900			1200			600			900			1200		
			Laser intensity [V]			Laser intensity [V]			Laser intensity [V]			Laser intensity [V]			Laser intensity [V]			Laser intensity [V]		
			3,0	3,5	4,0	3,0	3,5	4,0	3,0	3,5	4,0	3,0	3,5	4,0	3,0	3,5	4,0	3,0	3,5	4,0
Laser angle (β) - α = 30°	3°	Threshold [-] 150																		
		400					A									B				
		600																		
	20°	Threshold [-] 150																		
		400					C									D				
		600																		

Fig 5. Planned parameter-combinations - every box represents one experiment

4.2. Results

To ensure an objective and useful evaluation of the test results, the test data have been analyzed by using a specific measurement model. This model consists of different high deviations between the ZMap and the dimensions of the real test pieces. The basis of this analysis is the frequency distribution of the ZMaps. The deviations are calculated from this distribution of high values (z-values) to the frequency distribution of the original test piece measurements. As a result of this analysis, qualitative conclusions such as a ranking of the best parameter combinations are possible. To ensure the second test requirement (detecting the position of continuous carbon fiber material) the results of the ranking have been combined with a ranking of a visual COP analysis. For this reason, comparisons between different geometries and different laser angles are not as precise as relations between results of experiments with the same test piece and/or laser angle. Figure 6 is showing the best parameter combinations for lowest measurement deviation and for best visual property for one of the 4 series of tests. Every ranking is related to a group of 27 experiments with a same test piece and same laser angle.

The main result of the experiment is the relevance of the threshold for a high quality of the COP and the ZMap. In general, higher thresholds (such as 400 W or 600 W) have the most positive effect of scanning SMC. Additionally, middle and long integration times (900 µs and 1200 µs), combined with ideal laser intensity have also a positive effect. In special cases, also a shorter integration time in combination with high laser intensity (4 V) could induce good results. An explanation for these relations could be the highly reflecting characteristic of SMC (additional the reflecting characteristic of the matrix of cured SMC): Using a higher threshold enables detecting only those scattered rays that have a higher intensity than the threshold value. With a higher threshold the contours are sharper and, therefore, the ZMap and the COP are more precise. The perfect combination of integration time and laser intensity has to compensate the fallen number of detected rays (caused by the threshold).

Experient No.	Laser angle α (β - α = 30°)	Laser intensity [V]	Integration time [µs]	Threshold [-]	Rank-number (1-27)	
					Dimensional accuracy	with additional visual quality
Geometry (test-piece) for cured SMC with UD-Tape						
A18	3°	4,0	1200	400	1	5
A12	3°	4,0	600	400	13	1
C14	20°	3,5	900	400	1	7
C24	20°	4,0	900	600	6	1
Geometry (test-piece) for semi-finished SMC with UD-Tape						
B14	3°	3,5	900	400	1	7
B24	3°	4,0	900	600	5	1
D15	20°	4,0	900	400	1	9
D25	20°	3,0	1200	600	8	1

Fig 6. Best parameter combinations for each laser angle and for each test piece

An additional finding is the insensitivity of the COP quality dependent on similar parameter combinations: Changing the laser intensity (e.g. from 3.5 V to 4 V) or changing the integration time of one of the parameter combinations in Figure 6, induces no significant deviations of the quality. None of the tested parameter combinations have optimum dimensional accuracy and perfect visual quality. For this reason the perfect parameter combination could consist of values between the two tested ones.

Both laser angles are convenient for scanning cured SMC and semi-finished material including continuous carbon fiber material. The number of undetected pixels, in general, is higher for carbon fiber material, than for SMC. These undetected areas are shown in figure 7 (black/dark blue points). However, with a high threshold and a convenient intensity/integration time (e.g. C24 or B24 as figure 7 shows), the continuous carbon fiber material position can be detected, but not the fiber orientation.

5. Comparison of thermography systems

As shown in the previous chapter the laser stripe sensor system is a valid method to check the surface quality but inapplicable for providing information from inside the specimen. This task can be realized by an active thermography system as described in chapter 6. This chapter deals with the following thermography systems including possible combinations with a laser stripe sensor system as there are possible interferences:

- Pulse-phase thermography with flash lamps
- Lock-in thermography with halogen lamps
- Laser-thermography (linear heater)
- Thermography with infrared heater (linear heater)

To compare these four possible solutions suitable criteria were identified. A short process time is a prior criterion for an inline-capable measurement system. Flexibility related to different geometries and dimensions of the parts is also of high importance. The additional effort to process and evaluate the measurement results compared to the basic system is another criterion. Especially relative movements between measuring system and object require a line-wise transformation of each single thermogram into a global coordinate system. Other criteria like the safety of the operator, assembly space, weight and the potential costs of those systems were evaluated as well.

Forestalling the following chapter, the combination of laser stripe sensors and active thermography system can work either simultaneously (parallel) or one after another (sequential). Flash lamps and halogen lamps applicate heat onto a wide surface and are suitable for a sequential work flow, whereas a laser or an infrared line heater are able to heat a restricted line and are more practical for a parallel workflow.

The evaluation of the four potential thermography systems regarding the defined criteria is presented in Table 1. The pulse-phase thermography with flash lamps is the fastest and most flexible system and, therefore, most suitable for an inline measurement system. Due to its short process time, it is also adequate for a combination with a laser stripe sensor system. The Lock-in thermography is the most time-consuming method, because the material needs to be heated over multiple periods, until it gets into a stable level in which the measurements can be made.

Due to the slow heat flow of the SMC in z-direction, long detection times are necessary to identify deep defects. To identify abnormalities in the heat flow during a relative movement between the measurement system and the object a reduction of the velocity is necessary. Therefore, the laser and the infrared heated system require a long time as well.

Because of the light impulse of the flash lamp the operator needs to wear safety goggles. The biggest impact on the costs of most of the systems is the IR camera. Additional costs appear especially with the use of a laser as a heat source. Besides the higher costs of the heat source itself, further modifications are necessary to fulfil the laser safety requirement of laser class 4 (for example special safety goggles and additional laser curtains). Even if the Lock-in thermography is well suitable for the used material, the high process time is unacceptable for an inline system.

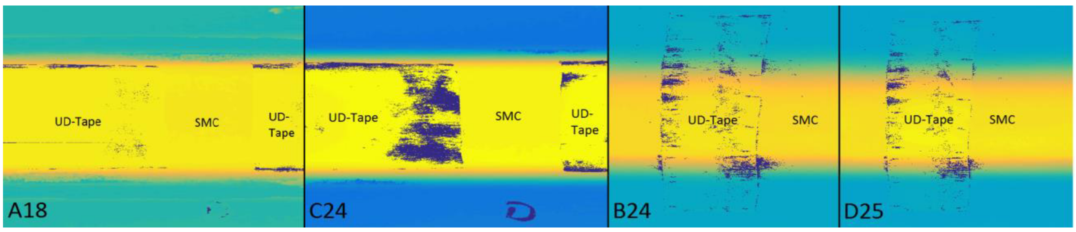

Fig 7. ZMap of the experiments A18, C24, B24 and D25

Table 1. Degree of fulfilment of different thermography concepts regarding important criteria (-- very low degree of fulfilment, o good degree of fulfilment, ++ very high degree of fulfilment)

	Process time	Flexibility	Evaluation effort	Safety	Space & weight	Costs
Pulse-phase thermography	+ +	+	+ +	o	-	+
Lock-in-thermography	-	-	+ +	+ +	o	+
Laser-thermography	o	o	-	- -	+ +	- -
Thermography with infrared heater	o	-	o	+ +	+	-

6. Experiments with thermography

6.1. Test execution

In order to be able to investigate internal defects, experiments were carried out with pulse-phase thermography. These tests were carried out both on cured components and on semi-finished material. In general, it can be said that in 1 mm depth a defect with 1mm diameter can be detected.

The experiments were carried out by means of the pulse echo method using an infrared camera of the type Flir SC5200. The distance between the camera and test object was 60 cm. Furthermore, two flash lamps with an electric energy of 6.4 kJ each were used.

In the evaluation, the frame rate is 5 Hz and in total 400 thermograms were recorded. In order to completely grasp the test piece, 4 pictures had to be made. The experimental setup is shown in Figure 8.

Figure 8. Test setup of thermography experiments

6.2. Results

During the examination of the semi-finished material, individual glass fibers were clearly visible. It was also possible to determine smaller air inclusions in the material.

For the already cured components, it is possible to detect different types of defects. By means of Fast Fourier Transformation, it is possible to detect defects near the surface as well as defects in the component interior. Thus, at a frequency of 1 Hz, resin accumulations and dry spots in the continuous carbon fiber material can be determined. It should be noted that at higher frequencies surface defects are detected and low frequencies show deeper errors.

At a frequency of 0.025 Hz of the phase images, clear air inclusions and delaminations in the discontinuous glass fiber material are clearly visible. Both phase images are shown in Figure 9.

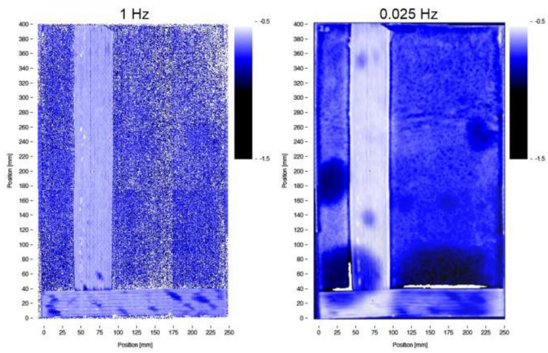

Fig 9. Phase Images with 1 Hz and 0.025 Hz

Thus, the analyses show that it is possible to detect internal defects in different heights beneath the surface by means of thermography, especially in cured test specimens, and to give statements about the condition of the component's interior.

7. Concept of multi-sensor measuring machine

As shown in the experiments before, the laser stripe sensor system is a valid method to check the surface quality of fiber reinforced plastics. To detect inner defects, like delamination or air inclusions, an active thermography system is a proper method.

As mentioned before, the combination of a laser stripe sensor system with an active thermography system in principle is possible in two ways. Both systems can work either simultaneously (parallel) or one after another (sequential).

The advantage of using both systems at the same time is the possibility for a prompt data combination and realizes a minimal reaction time. However, the process velocity needs to be synchronized and interferences between the measurements are possible. By using the systems in a sequential work process a synchronization is unnecessary and interferences impossible. Because of the separation, a higher process time is expected.

Whether a parallel or sequential workflow is possible depends on the type of heat source. Besides the completely different physical mechanisms of those heat sources, they also vary in their range of influence on the laser stripe sensors system as well as the specimen.

Figure 10 shows a conceptual visualization of a laser stripe sensor system (green) combined with an active thermography system (blue). A flash lamp (1) applies heat to the SMC-part (5) and the IR camera (2) detects the heat flow. For the detection of the surface quality, two sets of laser stripes (3) and cameras (4) are used.

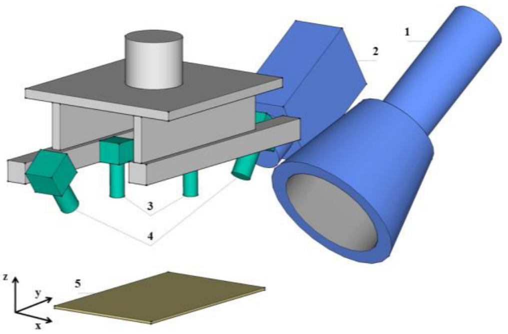

Fig 10. Concept of a laser stripe sensor system combined with pulse-phase-thermography

Thus, a combination of both systems enables a full quality control of SMC-parts. Due to the non-destructive, non-contact, fast and automatable procedure of both systems, they fulfil the basic requirements for an inline quality control system.

8. Conclusion and outlook

The investigations on laser triangulation and thermography have shown that both the semi-finished material and the cured components can be measured effectively with these methods. However, it becomes clear that thermography is to be applied rather to cured components, since typical internal defects can be detected. The shape and contour accuracies have to be recorded with the laser triangulation.

The combination of both systems would enable a holistic quality assurance and provide not only information about the existence and the location of single defects in the components but also about their relative position to each other. Thus, there is the possibility to further classify faults and to judge them according to their possible impact on the entire component. For this purpose, the conceptual considerations have to be implemented constructively in order to expand an existing laser triangulation system with a thermographic system. A significant added value can be realized by the subsequent data fusion. The data is not only combined but conclusions are drawn from the combination. For this purpose, an intelligent evaluation of the data has to be developed.

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