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Effects of Process Parameters on Intimate Contact Development in Laser Assisted Fiber Placement

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ABSTRACT

Intimate contact development has been considered as one of the principal mechanisms for consolidation during the automated fiber placement process. This work aims to investigate the effect of process parameters of LAFP on intimate contact development. Effects of nip point temperature, tool temperature, compaction pressure and placement speed on intimate contact development is experimentally investigated. 1-layer, unidirectional strips of CF/PEKK material are placed with different process parameters on a flat tool surface. Based on the observations, the concept of *effective intimate contact* is introduced and used to assess the degree of intimate contact. The results suggest that the effect of compaction pressure is linear whereas the effects of the placement speed is non-linear.

INTRODUCTION

Thermoplastic composites have drawn significant interest in the aerospace industry for their infinite shelf life, high damage tolerance, high impact resistance, chemical and solvent resistance, weldability and recyclability [1]. Automated fiber placement (AFP) has been identified as a promising manufacturing technique for thermoplastic composite structures. Reduction in labor hour costs, lower material scrap rates and higher repeatability are the main advantages of AFP [2]. With the introduction of heaters with high energy intensity such as diode laser heaters, in-situ consolidated structures are aimed.

Interlaminar voids are one of the key aspects to determine the resulting quality of in-situ consolidated parts. The air is entrapped when two rough composite surfaces develop intimate contact during compaction. Due to the high viscosity of the thermoplastic resins, even at high temperatures, the gaps between two adjacent layers cannot be filled with molten matrix. Irregularities on the composite surface must be deformed under the compaction pressure [3]. When the two composite surfaces are fully deformed and the air in between is fully evacuated, it is assumed that full intimate contact is developed at the interface. The common approach to explain how intimate contact develops is based on the squeeze flow of the surface asperities [3–6]. Such theories combine the compaction force, an idealized description of the composite surface and the viscosity of the composite to find the degree of intimate contact given the temperature and pressure history of the process.

Effects of process parameters of LAFP on intimate contact development have been studied quantitatively by a few researchers so far [7–9]. Laser power, placement speed, compaction force and heated length are determined as the most influential parameters on intimate contact development. In general, increased laser power, compaction force, heated length and decreased placement speed promote intimate contact development. However, a concluding experimental study on the effect of process parameters has not been demonstrated yet.

Experimental determination of the degree of intimate contact is a very important topic since it forms the basis to validate the intimate contact models. Different methods, as well as different specimen types have been used to measure the degree of intimate contact of thermoplastic composite laminates. C-scan [4,6], X-ray computed tomography [10] and cross-sectional microscopy [7,9] were used to evaluate the final degree of intimate contact. In the studies mentioned so far, the degree of intimate contact was measured at interfaces, where two composite surfaces meet. However, the intimate contact models were developed based on the flattening of a single surface against a rigid surface. This makes it more important to observe what happens at a single surface. To the authors' best knowledge, the only study which investigated the compaction of a single ply is the work of Lee and Springer [3]. However, the details of how the intimate contact was measured was not mentioned.

This work investigates the effect of process parameters on intimate contact development during LAFP experimentally. 1-layer, unidirectional strips of Tencate TC1320-1 AS4/PEKK material are placed with different nip point temperature, tool temperature, compaction pressure and placement speed on a flat tool surface covered with high-temperature resistant thermalimide film. Later on, pieces from the mid-section of the strips (where the process is assumed to reach the steady state) are cut and images are taken from the heated and compacted surfaces of the samples with an optical microscope. A new methodology to measure the degree of intimate contact from planar images of the compacted surfaces of a single ply is proposed.

EXPERIMENTAL METHODOLOGY

Fiber Placement System

Fiber placement experiments were conducted at Netherlands Aerospace Center (NLR). A 6 axis articulated robot on a linear axis provided by Coriolis is used. The machine is able to deliver 8 ¼ "(6.35 mm) tows simultaneously up to 800 mm/s placement speed. The end effector is equipped with a 6 kW Laserline LDF series diode laser system and an optic lens which creates a 56 x 28 mm rectangular illuminated area at the focal length. A 60 shore hard, 70 mm diameter conformable compaction roller is installed on the machine. Figure 1 depicts the fiber placement system used for this study.

Specimens for Intimate Contact Investigation

The material used in this study is TC1320-1 CF/PEKK supplied by TenCate, in ¼" slit tows. 8 tows with cross-sectional dimensions 6.35 x 0.15 mm were placed next to each other simultaneously along 1000 mm-long strips on a flat tool with each combination of process parameters in Table I. The tool surface was covered with thermalimide film in order to reduce the possible effects of the scratches on the tool on the degree of intimate contact measurements.

Table I. Process parameters used in the experimental study

Nip Point Temperature Target (°C)	Mold Temperature (°C)	Compaction Force (N)	Placement Speed (mm/s)
380	20	100	100
400	155	400	200
		800	400
			800

Process Temperature Measurement

The surface temperatures of the visible nip point of the tape were measured using a FLIR SC325 long wave infrared (LWIR) camera. The apparent emissivity of the material was calibrated according to the ASTM E1933 standard. A single layer of material was placed on the tool surface and a thermocouple was attached on the material surface. The material was heated by heating the tool and sufficient time was given to reach the steady state in the material. The end effector of the tape placement robot was positioned such that the thermal image was similar to actual placement conditions. Thermocouple readings were compared with thermal image readings of the same location. The calibration was performed around 220 °C and the apparent emissivity was found to be 0.85 for the CF/PEKK material. The power levels required for each placement condition were determined by trial placements and this fixed power value was used for the actual placements.

Measurement of Pressure Under the Compaction Roller

Although the process is controlled by the so called “compaction force”, the actual pressure under the compaction roller is unknown. Fujifilm Prescale LLW pressure sensitive films were used to measure the pressure under the compaction roller. Pieces of pressure sensitive film were fixed on the mold and different compaction forces were applied with the placement robot statically. A force range of 100 to 800 N was covered with steps of 100 N. Then, the dimensions of the stains on the pressure films were measured. It was assumed that the pressure distribution was uniform and the applied force was divided by the measured area to calculate the compaction pressure.

Optical Microscopy for Measurement of Intimate Contact

Samples from the mid-section (where the placement process is assumed to reach the steady state) of the strips were cut, as shown in Figure 2. This was done to isolate the possible effects of the acceleration and deceleration phases of the placement head. Degree of intimate contact of the samples was measured by taking images from the tool side of the surfaces. A Keyence VHX-2000 system with a VH-Z100 lens was used for the measurements. 5 images were taken for each specimen with 200x zoom (image size approx. 1 mm^2). Degree of intimate contact was determined using the grayscale value histogram analysis of the images. Two classes of histograms were observed. The first class of histograms belonged to the samples which have significant amount of resin rich area on the surface after compaction. There were clear peaks which could be used to separate the area in intimate contact from the rest. The second class of histograms were observed for samples with low amount of resin on the surface after compaction. Only a single peak was present in these histograms, making it difficult to set a threshold value. In such cases, the threshold was determined based on the point where the slope of the curve is the closest to zero after the first peak. Due to the morphology of this specific material, this selected area included dry fibers in addition to the compacted resin-rich areas. The resin-rich area on the surface is a pre-requisite for strength development between the subsequent layers, which is explained with the autohesion theory [11]. Therefore, degree of intimate contact is meaningful if it consists of resin rich areas only. In an attempt to eliminate the dry fibers from the area selected with the use of the histogram, all areas smaller than 500 μm^2 were excluded. This value was found to be appropriate for selecting the resin-rich areas as a result of trials with different threshold values on many images. The ratio of the remaining resin-rich region to the whole area of the image is designated as the *degree of effective intimate contact* in this work.

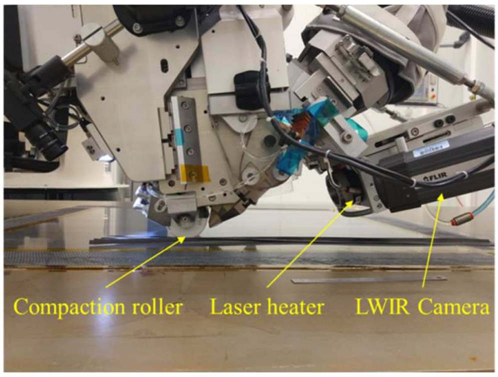

Figure 1. The fiber placement system used in the experiments

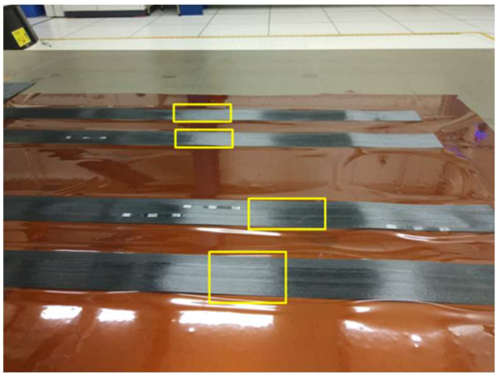

Figure 2. Portions of strips for degree of intimate contact measurements

RESULTS AND DISCUSSIONS

Pressure Measurement

The results from pressure measurements are summarized in Figure 3. The relationship between the compaction force and the compaction pressure is non-linear. As the compaction force increases, the contact area also increases due to deformation of the conformable roller. This prevents the pressure to increase proportionally to the compaction force.

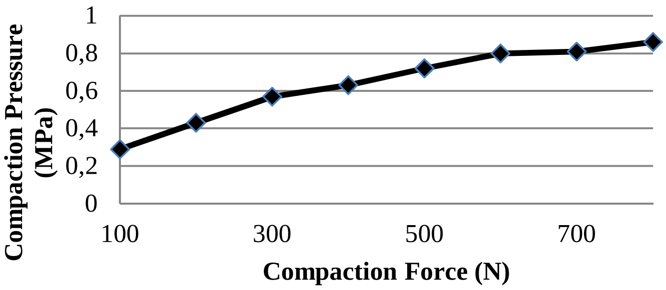

Figure 3. Compaction pressure under the compaction roller at different compaction forces measured with pressure sensitive films

Degree of Intimate Contact for Different Process Parameters

The results from degree of effective intimate contact measurements are summarized in Figure 4 (cold tool) and Figure 5 (hot tool). Typical images of different effective intimate contact levels are shown in Figure 6.

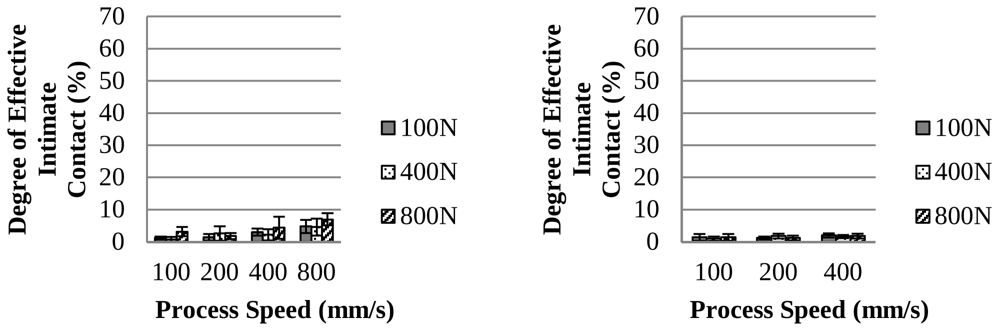

Figure 4. Degree of effective intimate contact vs. placement speed and compaction force- Tool temperature: 20 °C. Left: aimed nip point temperature 380 °C, right: aimed nip point temperature 400°C. Error bars indicate standard deviation.

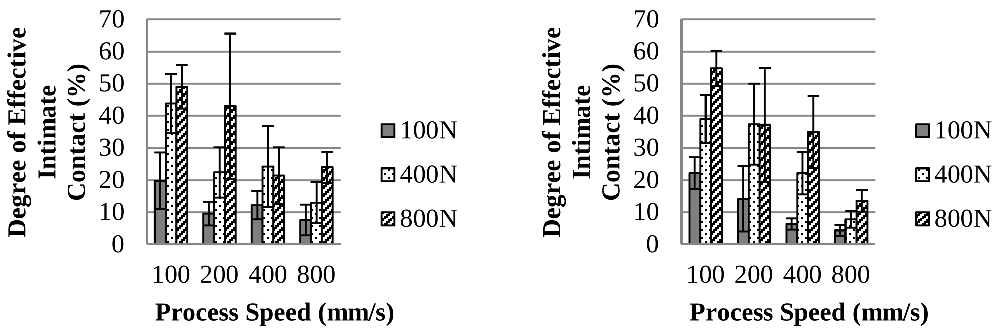

Figure 5. Degree of effective intimate contact vs. placement speed and compaction force- Tool temperature: 155 °C. Left: aimed nip point temperature 380 °C, right: aimed nip point temperature 400°C. Error bars indicate standard deviation.

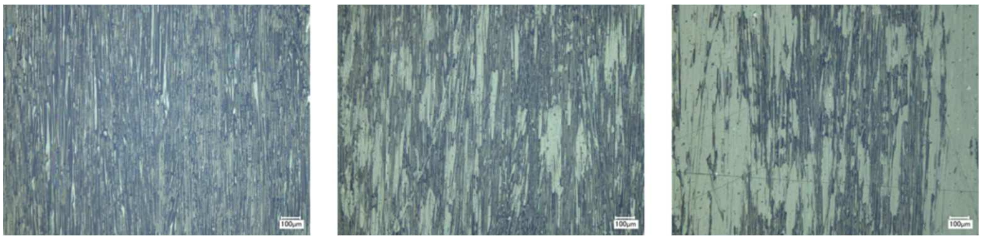

Figure 6. Representative surface micrographs for different levels of effective intimate contact: Left: 1%, middle: 23%, right: 57%.

Analysis of variance (ANOVA) is used to evaluate the effects of the process parameters given in Table I on the mean of the degree of effective intimate contact measurements given in Figure 4 and Figure 5. Matlab function *anovan* is used for this purpose [12]. Outputs of this function are p-values for each process parameter. p values smaller than 0.05 imply that the mean response of the specific parameter is different from the mean of all data within a confidence interval of 95 %. Table II shows the result of the analysis.

Table II. Results of the multiway ANOVA. $p<0.05$ means that the effect of the parameter or the interaction is statistically significant.

Source	**p-value**
Table temperature	0
Compaction force	0
Placement speed	0
Nip point temperature	0.3684

The effect of table temperature is immediately apparent as the effective intimate contact levels of samples which were laid down on the cold table (Figure 4) are very low compared to the ones placed on the hot table (Figure 5). This can be attributed to the heat sink effect of the cold table, which causes very fast cooling and prevent effective intimate contact development. Also, unlike the case of hot table, there is no clear trend showing the effects of compaction force and placement speed for the cold table. Because of this, the effects of the parameters will be discussed only over the case of hot table for the remainder of this section. This is also more relevant to the actual fiber placement process, where the substrate also reaches high temperatures.

Interestingly, the aimed nip point temperature did not cause significant changes on the degree of effective intimate contact. Although the squeeze flow viscosity of AS4/PEKK material was shown to decrease more than twice when the temperature was increased from 380 °C to 390 °C [13], this decrease was not reflected in the form of an increase in degree of effective intimate contact. A possible reason of this discrepancy might be the temperature controlling method. Thermal camera measurements can be affected by the emissivity value and the mirror-like reflections on the composite surface at the operational wavelengths of the camera. Such effects introduce uncertainty on the actual temperature reached at the nip point. From the experimental results, it can be discussed that a difference of 20 °C for the process control temperature is not sufficient to create significantly different effective intimate contact levels for this material system.

For a quantitative analysis of the effects of the compaction force and placement speed, the data in the plots on the left and right in Figure 5 is combined, i. e. the mean and standard deviation of all data with a compaction force of 100 N or a placement speed of 100 mm/s are re-calculated and this is done for all compaction forces and placement speeds. Figure 7 shows the combined data with a slight modification. The compaction force values are replaced with the equivalent pressure values from Figure 3. Examining the effect of compaction pressure on effective intimate contact development (Figure 7-left), a linear relationship between the compaction pressure and degree of effective intimate contact is observed. Note that this relationship holds for the compaction pressure instead of the compaction force due to the non-linear relationship between them. This observation contradicts with the current intimate contact models [3,6], where the degree of intimate contact is a function of the fifth root of the compaction pressure. When the effect of the placement speed is investigated (Figure 7-right), a non-linear relationship is apparent. Keeping the nip point temperature and compaction pressure constant, increasing placement speed reduces the compaction time. This observation confirms the non-linear evolution of intimate contact with respect to time as shown in literature [3,6,8,10].

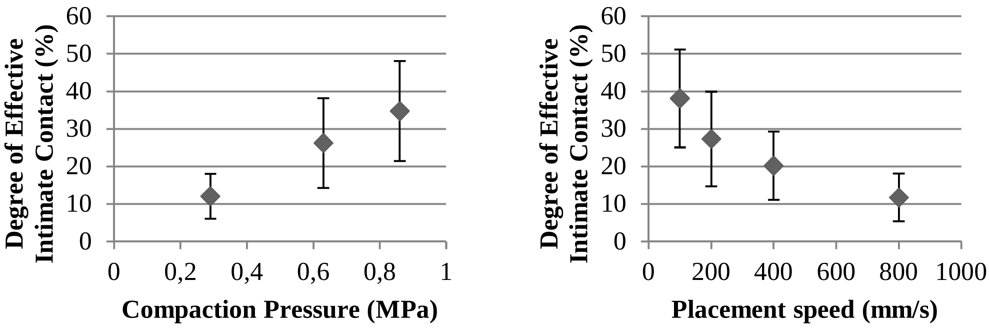

Figure 7. Overall effects of significant process parameters on the degree of effective intimate contact. Left: compaction pressure, right: placement speed.

CONCLUSION AND FUTURE WORK

In this work, the effects of LAFP process parameters on intimate contact development are experimentally investigated. The amount of resin on the compacted surface is the basis for healing and should be separated from the dry fibers when the intimate contact is experimentally measured. In order to do that, the term *effective intimate contact* is proposed and a methodology to obtain it from surface micrographs is proposed. Effective intimate contact measurements suggest that the effects of compaction pressure is linear whereas the effects of placement velocity is non-linear.

Future work includes a more detailed investigation of effective intimate contact development. A model to predict effective intimate contact formation will be developed.

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