# DEVELOPMENT OF A NOVEL CONSOLIDATION PROCESS FOR CONTINUOUS-FIBER-REINFORCED THERMOPLASTICS

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## Abstract

Consolidation is an essential process step in thermoplastic tape laying. In the present study it has been shown that an inert atmosphere like nitrogen or a vacuum reduces degradation of the material during this process. Based on these findings a novel consolidation approach was developed, in which a vacuum is used to apply pressure to the laminate while infrared radiation heats the thermoplastic material through a transparent mold wall. Beside radiation power, the thickness of the mold wall is a major influencing factor on the cycle time. For thin mold walls, cycle times below one minute for the whole consolidation step can be achieved.

## 1. Introduction

Depending on the quantity, the manufacture of parts from unidirectionally reinforced thermoplastic tapes (UD tapes) can be achieved using different approaches. For high volume applications, a fast tape laying machine like the Fiberforge RELAY® technology can be used to create a near net shape tailored blank out of locally welded UD tapes (Figure 1 - Step 1). Before the final forming step (Figure 1 – Step 3) can be carried out in an injection or compression molding machine, all entrapped air between the plies must be removed through a consolidation step (Figure 1 – Step 2). This process ensures repeatable forming behavior and is fundamental for void-free parts [1].

Different technologies can be used for consolidation, e.g. autoclave, double belt presses (isobaric or isochoric) or hydraulic presses. Depending on cycle time and consolidation quality, a suitable process can be chosen. If good mechanical material properties and low process cycle times are required, common technologies are generally expensive in terms of equipment and process costs. This was a motivation for the development of an innovative vacuum-based consolidation process, which applies pressures of over 1 bar to the tailored blank without using a cost-intensive autoclave or press system.

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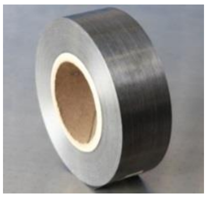
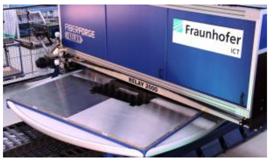
| Step | Input | Process | Output |
|---|---|---|---|
| 1. Thermoplastic tape laying |  |  |  |
| 2. Consolidation |  |  |  |
| 3. Forming |  |  |  |

**Figure 1.** Process chain for manufacturing UD tapes [2]

## 2. Consolidation

In the field of thermoplastic processing, consolidation means the production of a monolithic structure through the cohesive joining of single layers by simultaneously reducing the porosity of the whole structure [3,4]. This process is dependent on three main process parameters: pressure (P), temperature (T) and time (t) (Figure 2).

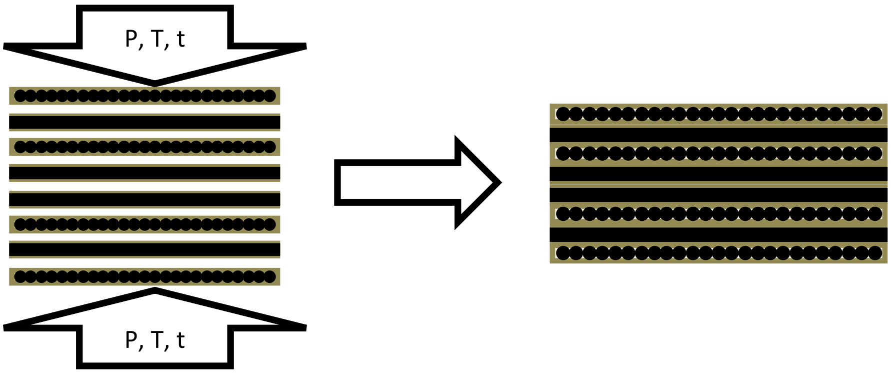



**Figure 2.** Principle of consolidation UD tapes (cross section)

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If the applied pressure is too low or irregular, lofting of the heated material occurs, which results in high porosity. If the applied pressure is too high, the fiber network is compressed, which decreases its permeability. Also, transverse fiber flow occurs, resulting in lower stiffness and strength in the fiber direction of the laminate [5,6]. Therefore the optimal pressure should be high enough to avoid deconsolidation and low enough to minimize transverse fiber flow. The application of a vaccum during the whole process reduces the overall porosity of the consolidated laminate [7].

In general high process temperatures lower the viscosity of the polymer, which enables faster consolidation. The temperature is limited by the melting point and degradation temperature of the specific material. Especially in case of polyamide 6, thermooxidation can occur at high temperatures. To identify the influencing factors on this process a thermal gravimetric analysis (TGA) was carried out, measuring the weight reduction of dried UD tape (BASF Ultratape Polyamide 6 CF) during storage at high temperatures (over the melting point) for 25 minutes. Three temperatures (230, 265, 300 °C) and two types of atmosphere (inert nitrogen and synthetic air) were varied. Figure 3 shows the result of this study: Generally lower temperature leads to less weight reduction. Inert atmosphere decreases weight reduction significantly on every temperature level.

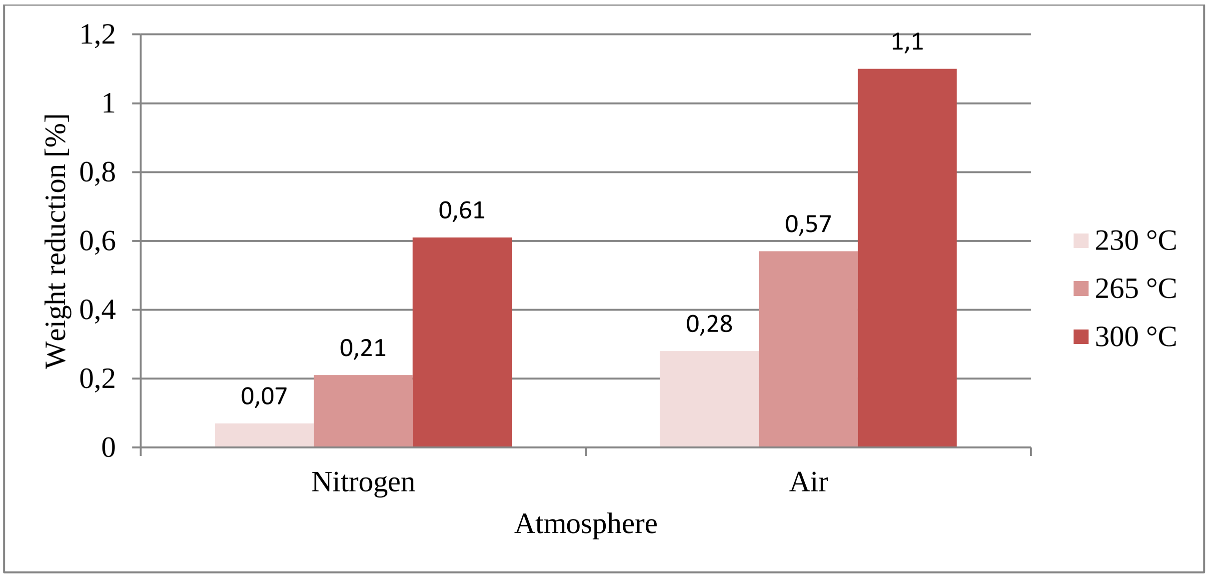


**Figure 3.** Weight reduction of UD tape under different atmosphere and temperature

To detect the emitted material, dried UD tapes were analyzed using pyrolysis-gas chromatography-mass spectrometry in nitrogen atmosphere. Three temperature levels and four different times at a given temperature level were investigated (Figure 4).

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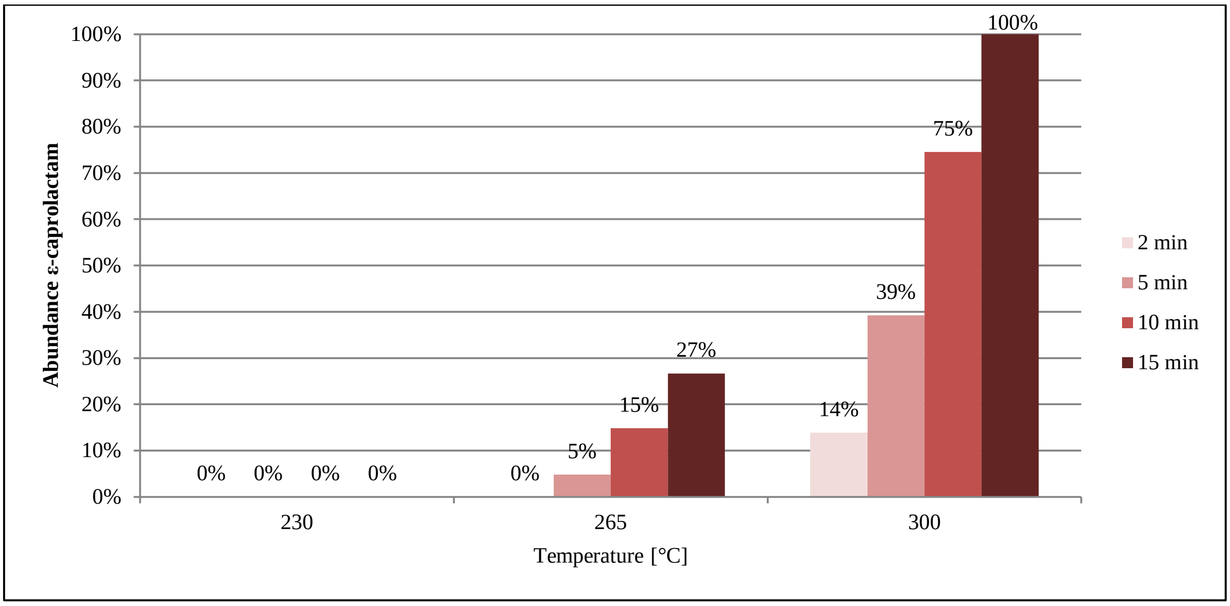


**Figure 4.** Standardized abundance of ε-caprolactam depending on time and temperature

The analysis shows that the emission of ε-caprolactam is the main reason for the weight loss during the process. The first ε-caprolactam could be detected by storing the UD tape for 5 minutes at 265 °C. The higher the temperature and the dwell time, the more ε-caprolactam was detected.

In conclusion, the porosity of the consolidated laminate can be reduced by applying a vacuum during the process. Generally an inert atmosphere (like nitrogen or a vacuum) minimizes the thermooxidation of UD tapes made from polyamide 6 CF during the process. Nevertheless, the dwell time at high temperatures should be as short as possible. To achieve this aim it is necessary to use a fast heating process, which allows the material to be heated under a vacuum atmosphere.

## 3. Process development

On the basis of these results, different concepts were generated and evaluated. Figure 5 shows the final concept: "**r**adiation-induced **v**acuum **c**onsolidation" (RVC).

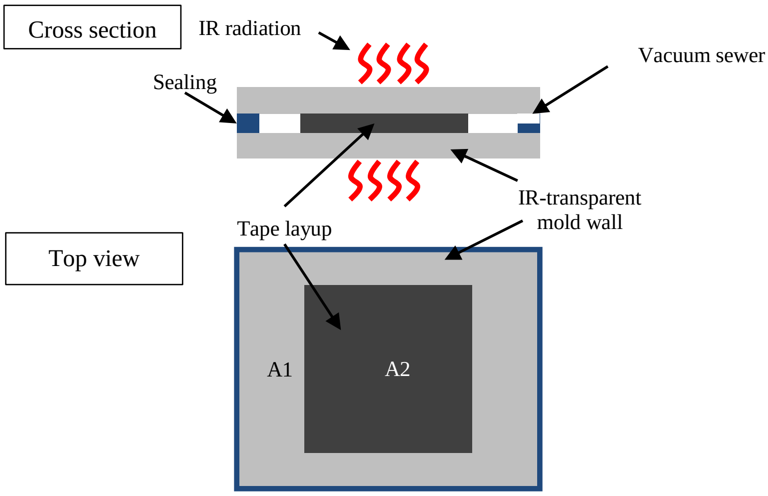


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**Figure 5.** Simplified principle of radiation-induced vacuum consolidation

In this concept, the tape layup is placed between two infrared transparent mold walls. These mold walls are sealed to each other with a compressible sealing which is mounted at some distance to the UD tape layup. If the resulting cavity is evacuated, the air pressure generates a force on the whole evacuated area (A1), which in turn generates a pressure on the smaller area of the layup (A2). This resulting pressure is enlarged with the factor A1 / A2 compared to the air pressure difference.

In traditional processes, the thermal conduction of the mold is used to heat the semi-finished products indirectly. This means that large thermal masses must be periodically heated and cooled during the process. For an efficient consolidation process with short cycle times and low energy consumption it is necessary to directly induce the heat into the semi-finished products. Therefore infrared (IR) heaters in combination with an IR-transparent mold wall are used for this new process (Figure 6).

**Figure 6.** Heating module of prototype at Fraunhofer ICT

This combination ensures short cycle times, as only small thermal masses are heated and cooled during the process.

Beside the performance of the infrared radiators, the transmission and thickness of the mold wall is the crucial parameter for short cycle times. Figure 7 shows the measured linear relation between heating time and mold wall thickness.

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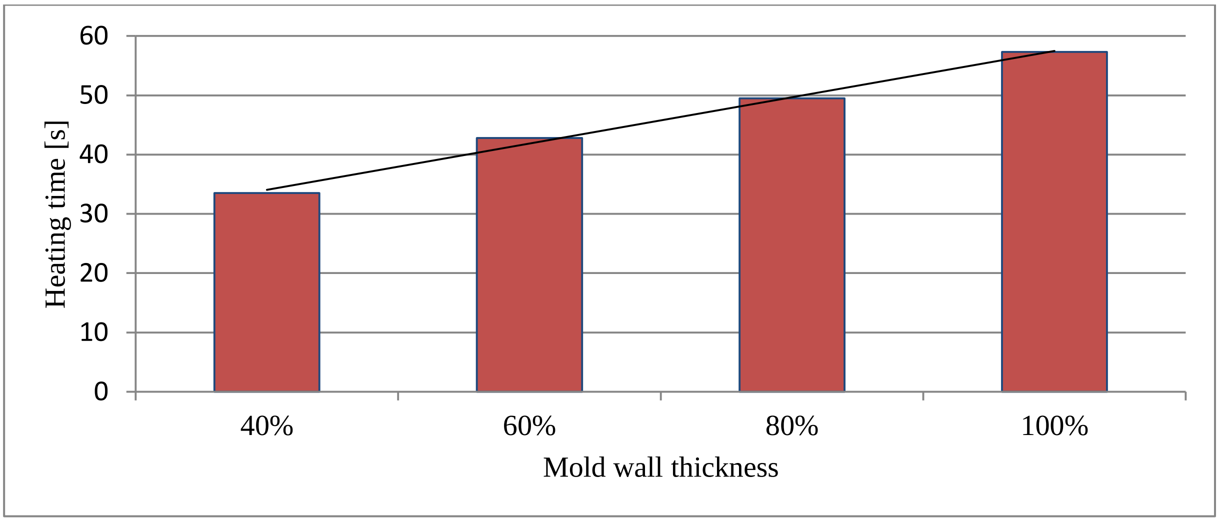


**Figure 7.** Heating time from 30 °C above melting point

As shown, the heating process from 30 to 225 °C of 2 mm thick layups (PA6-CF) can be completed in less than 35 seconds. In order to weld together the layup of different individual impregnated layers, a very short time period over melting temperature is necessary for autohesion to take place if intimate contact exists [8,9].
In order to cool the system, forced convection is used for the prototype, as this method does not apply any irregular pressure or pollute the surface of the mold. For higher cooling rates, water could be introduced directly into the nozzle.

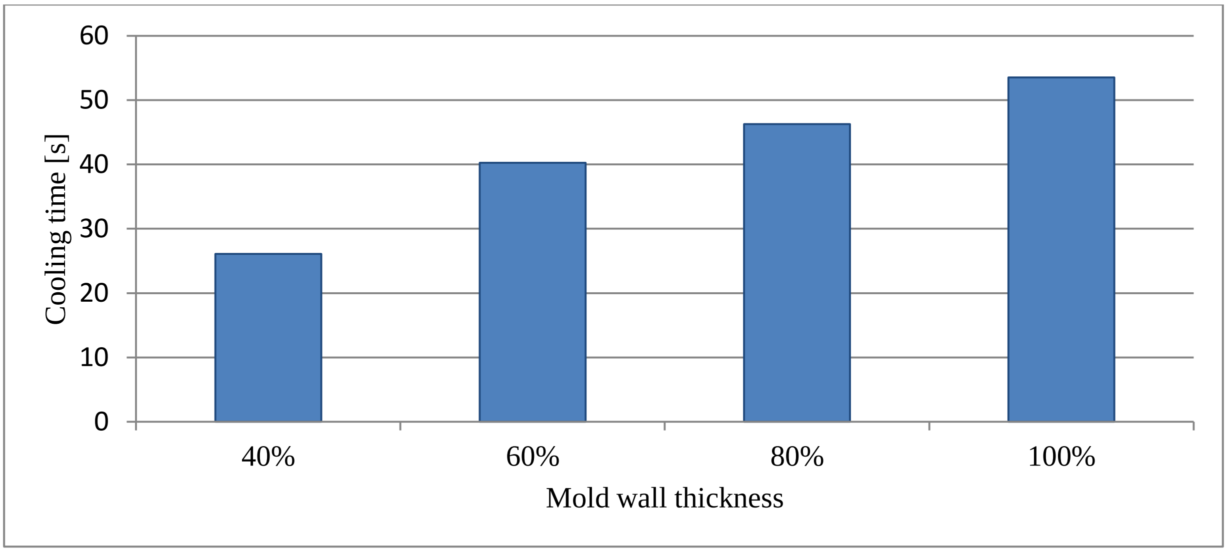


**Figure 8.** Cooling time from molten state (225 °C) under recristallisation temperature

Figure 8 shows the cooling time from a completely molten state at 225 °C to a solid state under forced convection. As the recristallisation temperature strongly depends on the cooling rate, this temperature could not be seen as constant. It was 183 °C for the 40% thick mold wall and 187°C for the 100% thick mold wall. At this temperature level the material had already been completely separated from the mold wall and could easily be removed from the mold. This hot demolding enables additional energy

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saving in the subsequent forming step, as the material still has a temperature near the melting point and only requires reheating above it.

## 3. Conclusions

In this paper, the influence of temperature, time and atmosphere on the degradation of carbon-fiber-reinforced polyamide 6 was investigated experimentally. It has been shown that an inert atmosphere like nitrogen or a vacuum reduces the degradation of this material. Based on these findings a novel consolidation approach was developed, using a vacuum to apply pressure to the laminate while infrared radiation is used for heating the material through a transparent mold wall. The influence of the mold wall thickness on the heating and cooling time was evaluated. For thin mold walls, total cycle times below one minute could be achieved for the consolidation step.

## Acknowledgments

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