EFFECTS OF FAST PREPREG PRESSING ON LAMINATE QUALITY AND MECHANICAL PROPERTIES

Oliver Rimmel[1], David May[1], Christian Gemperlein[2] and Peter Mitschang[1]

[1] Institut für Verbundwerkstoffe GmbH, Erwin-Schrödinger-Str., Geb. 58, 67663 Kaiserslautern, Germany, Corresponding author: oliver.rimmel@ivw.uni-kl.de

[2] all ahead composites GmbH, Benzstraße 5, 97209 Veitshöchheim, Germany

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ABSTRACT

This study aims to save time and energy in the curing process for prepreg materials, especially in out-of-autoclave applications. A detailed thermal analysis of a variety of prepreg materials has been conducted to define the time needed for full curing. As it was found that a high amount of curing takes place in a short time span (comparable to Pareto principle), investigations of the dependency of laminate properties on curing temperature and degree of cure have been conducted by producing sample plates and testing their mechanical properties. In conclusion, it was found that laminate properties comparable to those achieved in autoclave processes can be reached with fast prepreg pressing while strongly enhancing process speed and economic efficiency.

1 INTRODUCTION

For the manufacturing of high performance parts, thermoset prepreg materials offer the best use of mechanical properties due to the high achievable fiber volume content and impregnation quality. State of the art processing involves the use of an autoclave which causes high part costs, due to long cycle times, resulting from the extensive preparation (e.g. application of vacuum bagging) and the long autoclave cycle itself [1]. Furthermore, a high amount of energy is consumed for heating, cooling, and air compression. Consequently, autoclave processes are only suitable for rather small series volumes and markets with rather high contribution margin [2].

Pressing processes, in which the prepreg material is cured under pressure in a heated press, are increasingly applied to overcome the drawbacks of conventional autoclave processes and allow usage for prepreg-based high performance parts in mass applications such as automotive or sports. With this approach, cycle times in the range of few minutes are easily possible. Yet, as most autoclave cycles are tremendously longer than needed for curing of the prepreg material, most prepreg manufacturers do not provide exact data for the required curing times of their materials. Also, as can be seen in Figure 1, the curing rate strongly decreases with increasing degree of cure. Hence, the target of the presented study was to evaluate the cycle time potential of fast prepreg pressing by optimizing process chain and process parameters.

PROCESS CHAIN FOR FAST PREPREG PRESSING

During the research project "ProLight", a new out-of-autoclave process chain for the manufacturing of hollow high performance bicycle parts has been developed. To achieve high process speeds, the material has to be cured as fast as possible without affecting mechanical properties. A severe drawback of autoclave processes is the high thermal inertia of the heavy machinery that limits heating and cooling speeds. For this reason, the mass of machinery parts that experience temperature changes in the developed process has been drastically reduced. In standard pressing processes, a tempered tool is used for curing the resin system. However, the internal heating and cooling significantly increase the amount of energy needed for heating and cooling as the tool has to be bigger and heavier for this purpose. Consequently, a different approach has been used for "ProLight". The used tools are very lightweight and small as they do not possess internal cooling or heating. After inserting the prepreg stacks, the tool is closed and transferred into a press with heating plates. These are operated at constant temperature during the whole process. By closing the press, thermal conduction heats the tool very fast and the curing process takes place. After curing, the tool is removed and the finished part can be demolded. Up to this point of time, only the amount of energy needed to heat the light tool has been used (when neglecting radiation and convection losses of tools and heating plates) and depending on part geometry and size, about 30% of energy can be saved compared to using an autoclave. This result can even be optimized when reusing the energy saved inside the tool. By putting the tool inside a cooling press, the heat can be transferred to a liquid cooling circuit and subsequently be used for preheating tools or in hot water preparation. A schematic overview of the process chain is depicted in Figure 1.

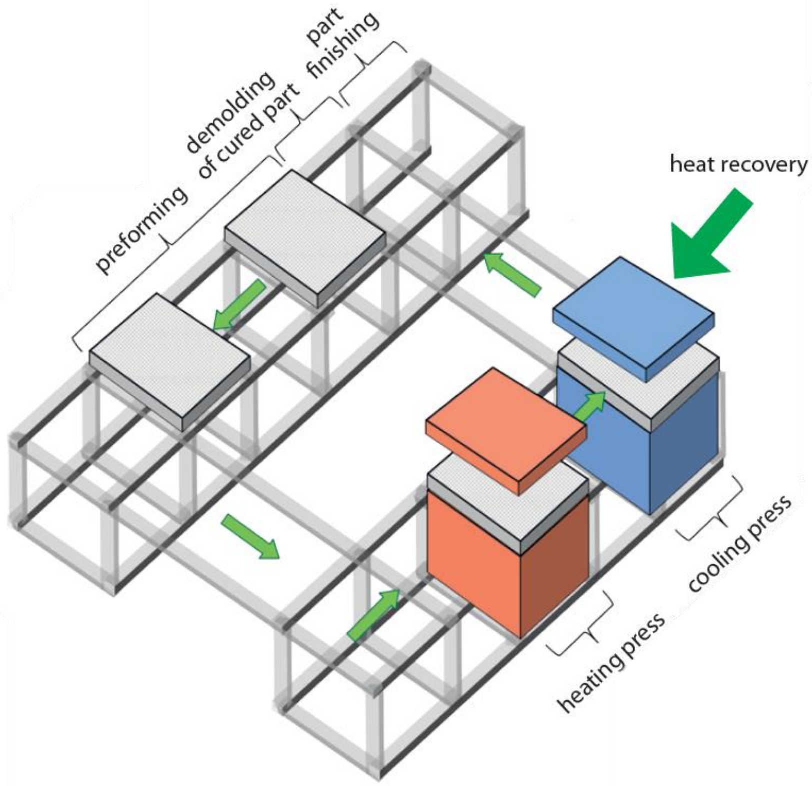

Figure 1: Process chain for efficient prepreg pressing

The process parameters in first trials were designed to reach a degree of cure of approximately 100%. However, it is questionable if this degree of cure is always necessary regarding the required mechanical properties. Lowering the target degree of cure to e.g. 95%, even faster process times could be achieved if it can be assured that no evaporation of volatile organic compounds and change of mechanical properties due to post curing will occur. In the conducted study, the influence of degree of cure and curing temperature material properties has been examined. For this purpose, a determination of mechanical properties depending on the reached degree of cure and the used curing temperature has been carried out by producing specimen plates in an isothermal press process which has been aborted at the relevant times to reach the desired degree of cure.

2 MATERIALS AND METHODS

To examine the influence of curing cycle on part properties, prepreg materials have been analyzed for their thermal properties. Subsequently, specimen plates have been produced and tested for their mechanical properties.

2.1 DETERMINATION OF CURING PROPERTIES AND MATERIAL CHOICE

In a first step for 7 different prepreg materials the dependency between curing temperature (120, 140 and 160 °C) and curing time has been characterized using Differential Scanning Calorimetry (DSC).

Two of the examined materials are standard autoclave prepregs, the other 5 are intended for fast curing cycles. The degree of cure of an epoxy prepreg material at a certain point of time can be approximated by comparing the released amount of exothermal energy with the total amount of energy occurring during full curing [3] (integration of curve). To obtain the dependency between curing temperature and progress of degree of cure, an isothermal measurement in DSC can be used, i.e. the measurement cell is heated to curing temperature as fast as possible and the temperature is kept constant until the heat flow has vanished. A measurement result with heatflow and deduced degree of cure over time is shown in Figure 2.

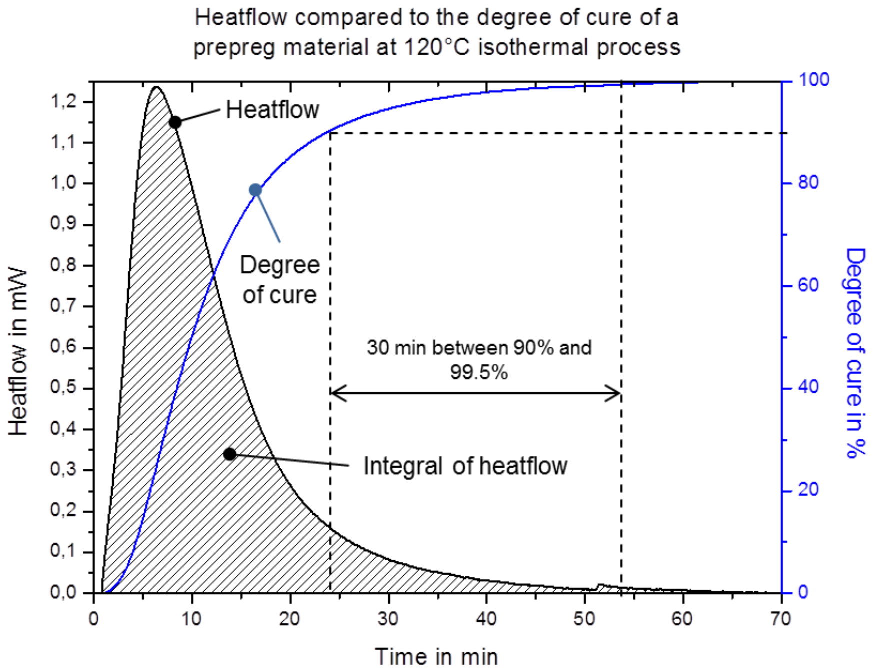

Figure 2: Heatflow compared to the degree of cure of the examined standard prepreg material at 120°C isothermal process

When comparing these curves for different temperatures for one specific material (Figure 3), it can clearly be seen that there is a strong increase of curing speed (i.e. curve slope) at higher temperatures.

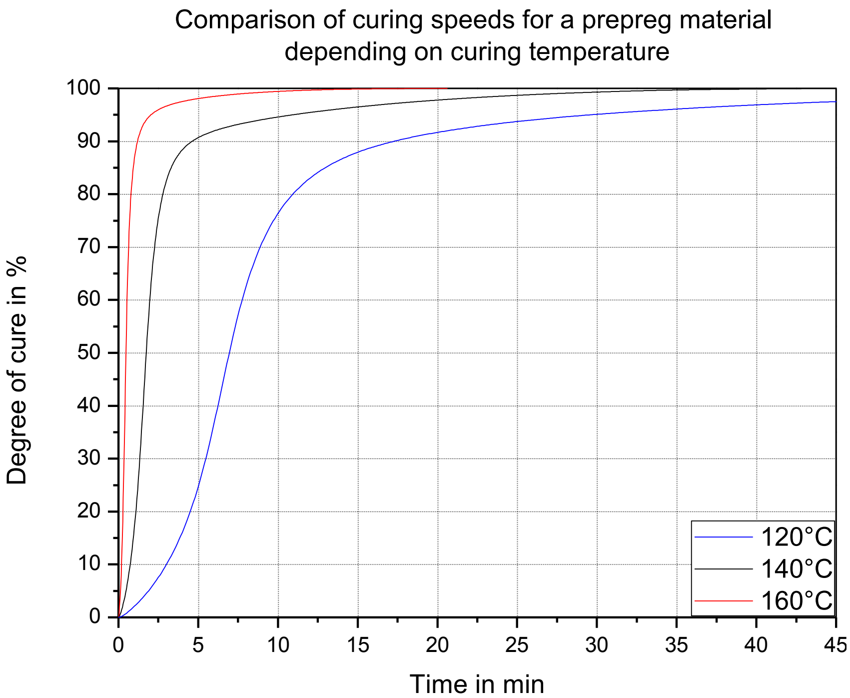

Figure 3: comparison of curing speeds for a fast curing prepreg material depending on curing temperature

2.2 LAMINATE MANUFACTURING

When manufacturing small specimen plates with a specified degree of cure, an exact compliance to the intended curing cycle has to be achieved. In a first step, cut-outs of the prepreg materials have been assembled to a prepreg preform (lay-up of (0/90)° woven fabric prepreg). The plate tool was pre-heated to the corresponding temperatures (120, 140 and 160°C) in an oven to assure fast heating of the material without thermal inertia effects. After inserting the prepreg stack, the tool was closed and transferred into a hot press immediately for curing at 5 bar (derived from autoclave process). The curing process is subsequently stopped after the specified time by demolding the material in hot state. Finally, the degree of cure reached for the plates was verified by measuring the glass transition temperature in DSC.

2.3 MECHANICAL TESTING

To determine the mechanical properties of the produced plates, tensile and bending tests have been conducted. In order to reach very exact process times for a defined degree of cure, fast heating, demolding and thus the use of small tooling inside a limited size press was necessary.

Due to the limited plate size of 97 x 97mm², a standard tensile test according to DIN EN ISO 527-4 with specimen dimensions of 250 x 25 x 2mm³ was not feasible. As the determined values are exclusively intended for comparison inside this test series, a specimen geometry of 97 x 4.5 x 2.3mm³ has been used. As fracture inside the clamping area could not successfully be prevented with these specimens, only the tensile modulus was calculated from these tests.

For the examination of laminate strength, a 3-point-bending test according to DIN EN ISO 14125 with a supporting width of 37mm for the laminate thickness of 2.3mm has been used.

3 RESULTS

3.1 THERMAL CHARACTERIZATION

In the DSC study, it was found that at temperatures of 120 °C the curing to 95% takes place between 17 and 44 min, depending on the material. Compared to this, the curing took only 3 to 15 min at 160 °C. A summary of the determined curing times can be seen in Figure 4.

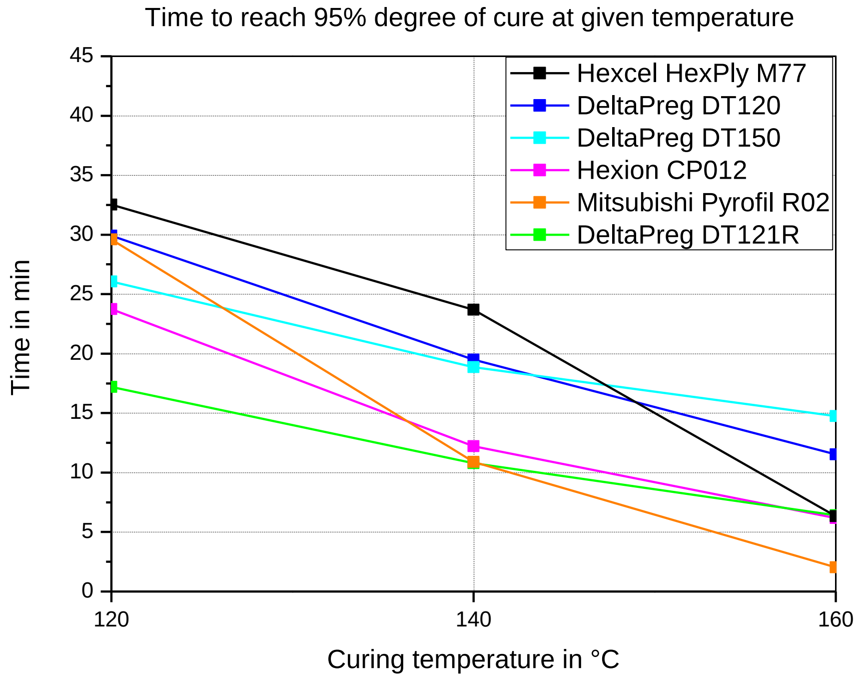

Figure 4: Time to reach 95% degree of cure at given temperature for multiple prepreg systems

All examined materials showed a remarkable decrease of the curing speed with increasing degree of cure comparable to the behavior of the material depicted in Figure 3. This is an expectable effect due to the lowering amount of available material for cross-linking. For example, time between a degree of cure of 90% and 99.5% makes up a fraction of the total cycle time between 57% at 120 °C (Figure 2) and 67% at 160 °C for the examined standard prepreg material. Thus, a high amount of time could be saved if a lower degree of cure would be sufficient to achieve the target mechanical properties. All in all, the study showed that fast curing processes are possible in principle not only with the special fast-curing systems, but also with standard prepreg materials.

3.2. MECHANICAL RESULTS

During mechanical testing, it was observed that the influence of the degree of cure can be neglected when conducting tensile testing in fiber direction (Figure 5, left), as almost no decrease of tensile modulus with lower degrees of cure was observed. This can be explained as the tensile properties of the material in fiber-direction are mostly fiber-dominated. Considering the bending strength (Figure 5, right), an incisive decrease with lower degree of cure can be stated, however, this influence is stronger for the higher chosen curing temperature of 160 °C than for 140 and 120 °C. Between the curing degree of cure of 90% and 95%, no significant enhancement in bending strength can be observed.

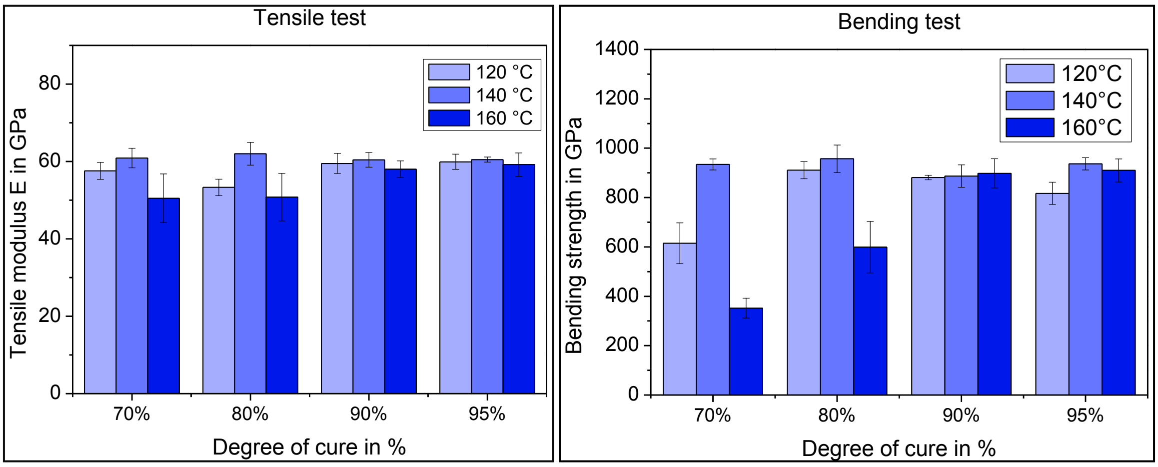

Figure 5: Mechanical properties of a prepreg material in dependency of degree of cure and curing temperature

When designing a process after these trials, no full curing – which consumes time and energy – has to be claimed for the examined material, as no further increase of mechanical properties can be seen beyond a certain point. Furthermore, depending on part geometry, the curing speed can vary inside one part due to uneven heating distribution. If a curing of 90% is acceptable, it could be sufficient to ensure a curing of the most critical areas up to this level to reach the desired properties while single areas would already exceed it.

3.3 TRANSFERRING TO FULL SCALE PRESSING PROCESS

To scale this process up from the small-scaled pressing plates, a process for larger scaled parts has been defined. During pressing trials, a hollow bicycle handlebar (Figure 6, bottom) has been manufactured using a press with heating plates.

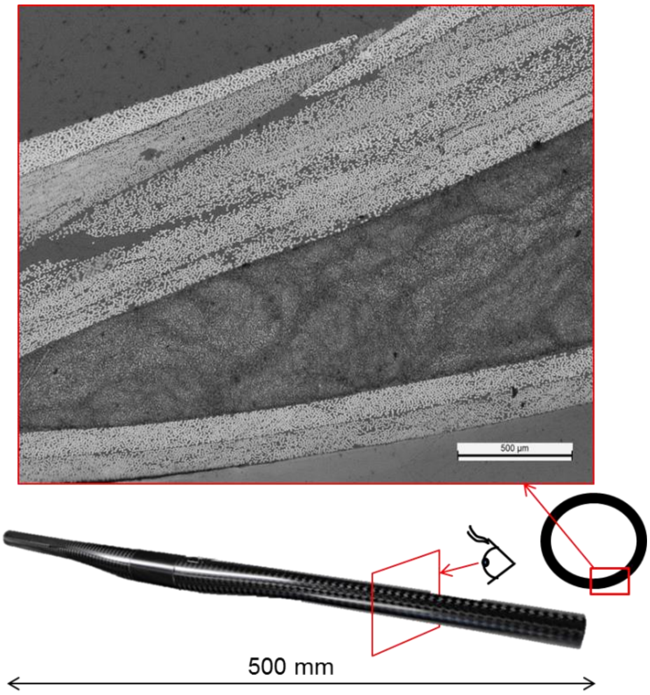

Figure 6: Microsection of finished bike handlebar after pressing process shows very good impregnation quality

After lay-up, the prepreg preform has been inserted into the mold and a blowing hose was added to apply the inside consolidation pressure. The cold tool was transferred onto the heating plate and the press has been closed to bring the upper heating plate in contact with the tool. It was shown that heating rates up to 30 K/min can be reached and that no overspeed curing of the standard prepreg material due to the exothermal reaction occurred. In total, a curing cycle of 22 minutes at a maximum of 160 °C was applied to a material which is specified for a curing process of 90 mins at 120 °C plus the corresponding heating and cooling ramp times in autoclave (total process time of ≈ 3 hrs). A dynamic measurement in the DSC showed no additional curing reaction after this process.

In order to aim at shortest cycle times in a pressing process, the exact temperature curve during heating has to be measured for the used tool. If this curve is known, a calculation of degree of cure using finite time steps can be approximated to further reduce process time. An exemplified measured curve for a pressing process for the bicycle handlebar is shown in Figure 7.

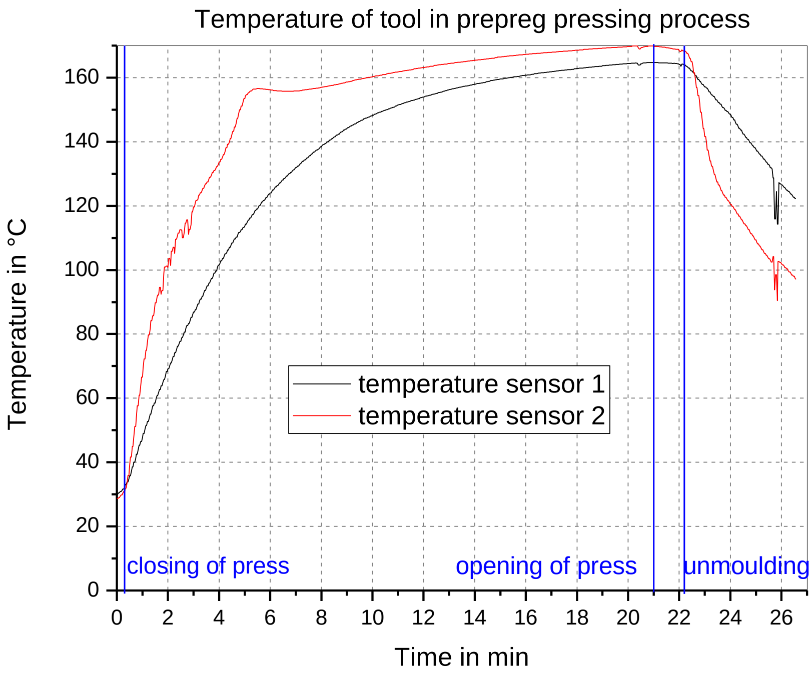

Figure 7: Temperature curve of tool in prepreg pressing process

4 CONCLUSIONS

Changing from an autoclave process to a pressing process for the manufacturing of parts from prepreg materials shows no significant decrease in part quality. During examination of the finished part, it was observed that surface quality and microscopic impregnation quality of the part were comparable to the reference autoclave part produced with the same tool and layup.
Still, the amount of costs and energy saved is tremendous. This potential can even be expanded when reducing the desired degree of cure to a value of 90%. Despite the tremendous time savings induced by this choice, comparable mechanical properties can be achieved.

In summary, the shown out-of-autoclave strategy allows the manufacturing of cutting-edge high performance composite parts for high batch sizes.

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