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IR-Thermoforming Window Design via a Thermal Approach: for CFRTP and Hybrid Thermoplastic Composites

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Thermoforming of continuous fibre reinforced thermoplastic (CFRTP) is a fast-manufacturing process conducted using rapid infrared (IR) heating of composite prepreg/laminate followed by shaping the product using a mould with geometry. There is a vast scope for the thermoforming process window design by considering the thermal aspects in IR heating and thermoforming process. A reliable thermal process design approach was established from the understanding of the thermal behaviour of material and mapping it to specific process control parameters to provide the right forming conditions for thermoforming. An in-depth correlation study of the material-process influence for thermoforming is presented. Thermal behaviour of the CFRTP was evaluated using commonly used diagnostic tools like TGA, DSC and DMA and a real-time temperature loss recording of the CFRTP to define the time period where thermoforming was feasible. This thermal approach can be used to determine the suitability of any thermoplastic composite material for thermoforming and define the suitable process window without trial and error. Application of this methodology was successfully demonstrated in thermoforming of CFRTP of different thermoplastic system as well as hybrid thermoplastic composites.

1. Introduction

In recent years, the automotive industry has shown increasing interest in the manufacturing processes of thermoplastic–matrix composites materials [2], particularly the thermoforming technique for its rapid cycle times and the possible conversion of pre-existing press equipment. Thermoforming is conducted using rapid infrared (IR) heating of plastic sheet/ CFRTP laminate, followed by shaping the product using a press mould. Depending on the material (neat thermoplastic sheet or fibre reinforced thermoplastic) and applied load, thermoforming process can be categorized into three types: vacuum forming, plug-assisted forming and pressure forming. As the name “thermoforming” implies, thermo- relates to heat and temperature; it is a temperature-dependent process. There is a vast scope for the thermoforming window design by considering the thermal aspects in IR heating of material, heat transfer during the sheet transfer from heating station to forming station and the thermoforming process.

The development of a thermoforming process is complex and costly to achieve by trial and error given the high material cost of CFRTP. Various research groups have investigated the heating stage in thermoforming, with majority of them focusing on the numerical approach to investigate the efficiency of IR heating and thermoformability of a material [3],[4],[5],[6].

In this work, we present a systematic approach derived from the understanding of the thermal properties of CFRTP and measured events of the thermoforming system to define the right process parameter window for thermoforming. Changes in heating parameters affected the material differently, and vice versa. An in-depth correlation study of the material-defined thermal process design for IR-thermoforming will be discussed. This paper shows that our thermal approach is highly versatile and can be suited to various thermoplastic system, through identification of the thermal properties of the matrix. In addition to CFRTP, the methodology was successfully extended to other forms of hybrid and sustainable composites. It is also a reliable screening tool that can be used to evaluate the thermoformability of any sheet material on a given thermoforming equipment.

2. Materials and Methodology

2.1 Thermal characterizations of polymer matrix

The thermoforming process is generally conducted in three stages: the heating stage, the sheet transfer stage, and the in press (moulding-demoulding) stage. The process window for thermoforming is bounded by four thermal behaviors, namely,

(i) Maximum forming temperature
(ii) Minimum forming temperature
(iii) Heat loss profile (most critical in defining the 'process window' for any material), and
(iv) Demoulding temperature

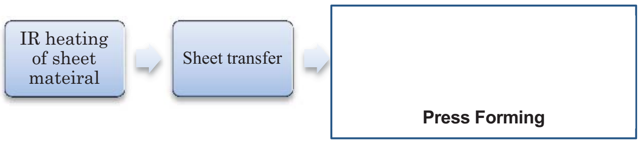

Fig. 1 Each stage in thermoforming is bounded by measurable thermal behaviors and events

It is imperative to assess the thermal behaviour of the polymer matrix since the forming temperature is the key parameter in thermoforming. 2x2 carbon twill laminates with Arkema's Elium™ resin (HAP608 CF3327-1) is used in this work to establish the methodology. Thermal tools including TGA, DSC and DMA are used to identify the thermal properties of the material.

The onset of matrix degradation generally limits the upper forming temperature the process. This value is determined via Thermogravimetric Analysis (TGA) by setting the CFRTP sample to degrade in air, ramping at 10°C/min to 900°C. The temperature where the increase in the rate of weight loss was first detected on the temperature-derivative curve was used to set the upper forming temperature.

In thermoforming, the material is heated to its softening point, after which it is shaped to conform the forming profile by employing pressure or mechanical forces [7]. The glass transition (Tg) and/or melting (Tm) temperature are determined using the modulated mode of Differential Scanning Calorimetry (DSC). Approximately 10mg of sample is sealed in an aluminium hermetic pan and heated at a rate of 5°C/min from 40°C to 250°C, with a modulation of ±0.5°C every 40s, to separate the reversible and irreversible heat flows.

There are many factors contributing to the optimization of thermoforming quality besides the laminate's temperature being one of the key contributors. McCool et al. [8] considered not only the laminate forming temperature but also the mould tool temperature in their process optimization for thermoforming of CF/PPS thermoplastic laminate. The recovery of the storage modulus, which can be determined using the Dynamic Mechanical Analysis (DMA), relates well to how polymer can retain its shape after demoulding. The composite specimen is heated from 35°C to 150°C at a rate of 5°C/min in dual cantilever mode, during which the physical response to cyclic mechanical displacement at a frequency of 1Hz and amplitude of 30μm is measured. In Fig. 2, the demoulding temperature is obtained from the derivative of storage modulus, at around 67°C where the recovery in stiffness of the 1.25mm thick Elium/carbon fibre composite laminate is at 85-90% of its peak, giving some flexibility for demoulding yet stiff enough to resist distortion under the demoulding forces.

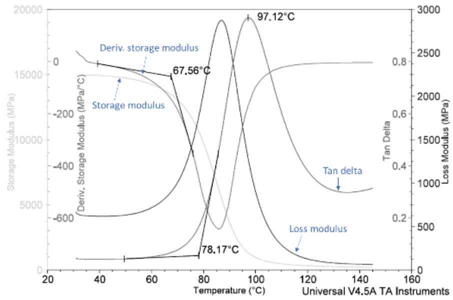

Fig. 2 DMA analysis graphs of a 4-ply Elium composite laminate

2.2 Thermal profiling of the composite laminate using FLIR camera

Having heat delivered to the sheet externally via infrared, rather than contact heating through the mould offers lower cycle time and reduced energy requirement. The control of heat transfer to achieve thorough and even heating, and the management of heat loss during sheet transfer from the IR heating station to the press forming station, are critical factors for high quality thermoforming. Having real-time, accurate thermal measurement and feedback control will aid this realization.

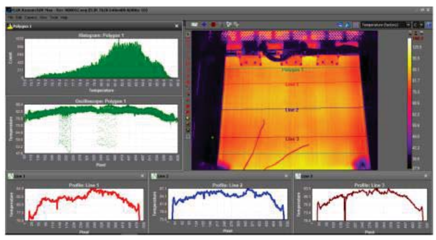

Fig. 3 Areal measurement of the IR heated laminate using thermal camera to record its heat distribution and heat loss profile

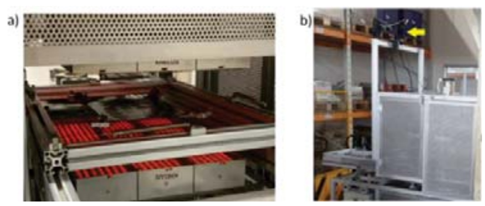

Fig. 4 a) CFRTP laminate suspended between the top & bottom heaters. b) FLIR camera setup for thermal measurement after heating.

A real-time thermal profile of a heated CFRTP is recorded using T6000 series FLIR thermal camera coupled with ResearchIR Max software (Fig. 3) to evaluate the surface distribution of the transmitted heat flux by measuring the laminate's surface temperature distribution . A recording function allows the mapping of material's temperature loss with time on transfer from the heating stage to moulding stage.

The experiment setup is shown in Fig. 4.

3. Discussions

3.1 Thermal Process Window Design for Sheet Heating and Transfer

Performing thermal characterizations are important, as product datasheets often provide a single value of glass or melt transition temperatures, which does not inform events such as degradation onset or stiffness recovery. When we carried out IR heating on the Elium composite laminates at 180°C – 200°C, at temperature as prescribed in TDS and in fact far below the onset degradation of the Elium resin at 315°C obtained experimentally, blistering on the laminate and delamination occurred. This phenomenon is associated with the early degradation of additives/carbon sizing, a minor event (<5% weight loss) which might have been overlooked but is quite a big trouble to overcome in thermoforming when we require aesthetic appeal and in terms of processibility.

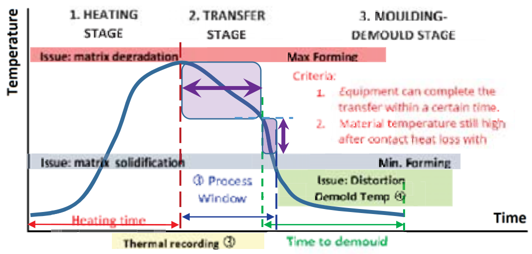

Fig. 5 Schematic presentation of the key thermal events in thermoforming that would define the process feasibility window [1].

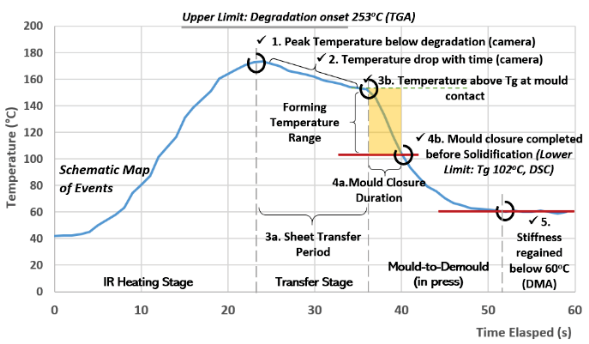

Fig. 6 Process feasibility window defined for the CFRTP studied.

Key thermal events at each stage in a thermoforming process are charted in Fig. 5. Heating stage and forming/moulding stage happen at two separate stations. Substantial heat loss is inevitable depending on the time factor and environment of transfer. In case the heat loss during sheet transfer is significant, 'overheating' the laminate could be done to ensure that the laminate is hot, soft and pliable enough to form when it reaches the press [3]. However, the 'overheating' is still limited by the maximum forming temperature, as well as the onset of any degradation event. In our thermoforming system, the transfer stage takes 6-8 seconds from the moment IR heaters is switched off to the time where mould is fully closed. In this process window timeframe, it is crucial to ensure that the temperature of the CFRTP does not fall below Tg (softening point). During the moulding stage, higher mould temperature is generally preferred to prevent resin solidification and matrix tear defects arising due to mould contact heat loss. On the other hand, for the product to be demoulded without distortion, the moulded product needs to be cooled sufficiently. The schematic map of events that applied this process window definition approach is plotted in Fig. 6 and showed that a feasible (yellow box) process zone was found and the CFRTP is thermoformable.

3.2 Cooling profile of a CFRTP laminate

In this section, we present the temperature loss profile study of an automotive CFRTP laminate (Stylight S C245-1, by INEOS Styrolution) considering the sheet transfer duration. Stylight S is a SAN thermoplastic-based composite which give a beautiful shiny finish, making it a good solution for aesthetic applications yet with substantial strength and stiffness (greater than polystyrene) [9].

The most basic control parameters of an IR radiation are energy, distance and time, with respect to the material absorbency of the IR wavelength received. SAN laminate is clamped between the top and bottom heaters as shown in Fig. 4(a), with working distance of 120mm from each side. The power setting for IR heaters were varied from 70% to 80% at 5% interval, with heating durations increased incrementally from 15 seconds. The minimum sheet temperatue before mould closing is recommended at 180°C – 200°C. During our heating optimization, slight fuming was observed when the laminate temperature gets closed to 200°C. We therefore limit the heating temperature at 190°C for processabilty of 1.2mm SAN laminate. The temperature recorded from the top surface of the SAN laminate is plotted in Fig. 8. The area demarked "Box 1" in Fig. 7 is where a forming profile resides, the region where we measured the temperature at 3, 5, 8 and 12 seconds interval, respectively.

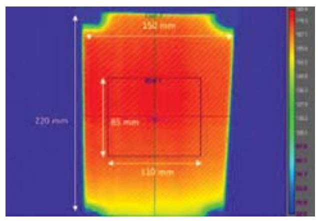

Fig. 7 Thermograph of an IR heated SAN laminate recorded using T6000 Series FLIR camera.

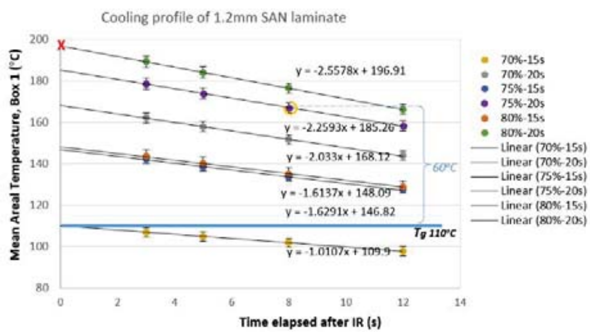

Fig. 8 Temperature profile of a 1.2 mm SAN laminate at varied IR heating conditions.

From Fig. 8, the SAN laminates showed a highly linear cooling trend for all the heating conditions. The gradient of the trendlines gives the rate of temperature drop in °C/s. If we look at 20 seconds heating duration, steeper temperature declines were derived from higher heating power settings as a percentage of the maximum power available (green 80% > purple 75% > gray 70%). The trend was also true for 15 seconds heating. In general, a higher heating power corresponds to shorter heating duration and faster cycle time. On the contrary, a low intensity slow IR heating can provide more time for heat soaking into the depths of the panel, so that the thermal release during sheet transfer would be slower. This is suitable for thicker CFRTP laminates or where long sheet transfer time is required, for slower temperature loss. 75% power 20 seconds heating would be the best option for heating 1.2mm SAN because the projected laminate temperature at time 0 second is about 185°C. At 8 seconds forming, laminate temperature will be around 170°C which is sufficient to prevent matrix solidifications when coming into contact with the warm tooling.

3.3 Thermoforming of other composite systems

Besides CFRTP, we extended the validation of this thermal design methodology to other composite materials includes natural fibre composites and hybrid composites. Hybrid composite laminates are made up of different material constituents such as carbon fibre, basalt fibre, coir and flax natural fibres, along with either polypropylene (PP) or polycarbonate (PC) polymer matrix. Our proposed methodology can be suited to various matrix system, for as long as the thermal properties of each constituent materials were identified and understood.

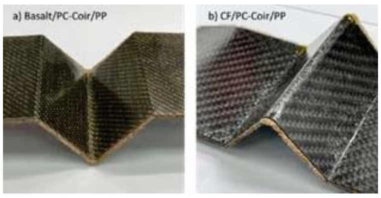

Fig. 9 Thermoformed of hybrid composite laminates, a) basalt/PC-Coir/PP -basalt/PC and b) CF/PC-Coir/PP-CF/PC

It is worth noting from the thermoforming trials that all the hybrid composites sandwiches have to be pre-consolidated before used for thermoforming. Attempts to thermoform un-consolidated stack of loose plies were unsuccessful because the thermoforming process was conducted below the melt temperature and therefore the resin flow and diffusion bonding would be insignificant. The thermoforming process presented in this paper only involved softening and shaping of the composites with little-to-no diffusion bonding at the ply interface nor consolidation during thermoforming step. It was also observed that the process temperature upper limit can be limited by many issues such as blistering, delamination, volatile emission, and natural fibre degradation, etc., hence resin melt temperatures were seldom attained. Fig. 9 shows the thermoformed samples using pre-consolidated hybrid sandwich laminates optimized through the thermal approach presented. The samples were heated under IR at the process setting of 85% power, 25 seconds, 120mm working distance from each side heater (PC and PP required same processing temperature at about 160-170°C), sheet transfer time of 8 seconds, formed at press setting of 11kgf and a cooling-demoulding time of 1 minute inside the 60 °C mould. Forming were successfully achieved.

4. Conclusions

Thermally, the heat transfer phenomena are complex during the thermoforming stages, from heating, transferring, to moulding and demoulding. Our thermal process window design methodologies derived from the fundamentals of the thermal behaviors of the material, served as an effective tool to evaluate feasibility of the process for any thermoplastic material, including biocomposites and hybrids. This simple method can help to ascertain the thermoformability of thermoplastic fibre reinforced composites without prior physical thermoforming trials required, leading to time and cost savings.

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