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In-Mould Gel-Coating for polymer composites

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Abstract

Surface coatings (gel-coats) are often used on commercial composite mouldings for cosmetic and/or durability reasons. They have traditionally been prepared in open moulds with styrene vapour allowed to escape to the workspace and environment. This paper considers the development of in-mould gel-coating processes. A Double Glass Plate Mould (DGPM) was used to prepare flat composite test panels. Laminates were manufactured by liquid composite moulding processes. Conventional hand painted gel-coat, innovative In-Mould Gel-Coating with a trilayer separator fabric (IMGC) or In-Mould Surfacing with a silicone shim (IMS) were studied. The surface quality of the final products was measured using a Wave-Scan device while the adhesion of the gel-coat was characterised by pull-off tests. The new processes offer reasonable properties in a cleaner, more controlled process.

Keywords: A. Polymer-matrix composites (PMCs); B. Adhesion; D. Surface analysis; E. Resin transfer moulding (RTM)

1. Introduction

The fibre reinforced polymer matrix composites industry recently had annual production of nearly 3 million tonnes of material in the United States of America [1] and over 2 million tonnes in the European Union [2]. The high-performance sectors (aerospace, biomedical and defence) make up a significant proportion of the economic value. More than 80% of the market mass is “commercial” mouldings (e.g. automotive, chemical plant, construction, marine, rail, and energy) which often have a gel-coat surface for cosmetic and/or durability reasons. The gel-coat is normally applied by hand- or spray-painting onto the open mould followed by gel hardening in the open tool before composite lamination. This leads to consequent elevated levels of volatile organic compounds (VOC) in the workplace and the environment, and risk of human error in the production process. Harmonisation of styrene occupational exposure levels across Europe is expected to settle on 20 ppm, which will be difficult to achieve with open mould processes.

Technologies for in-mould gel-coating have recently been reviewed by Rogers et al. [3]. The principal drivers for change are the legislative framework for worker health, the environment and economic considerations. The principal in-mould gel-coating techniques are either insertion of a coating film into the mould tool or mould opening to create space for the injection of the coating. The latter technique is not suitable for surfaces/draft angles normal to the mould opening direction as little or no additional space is created in this plane.

Two recent patent publications have proposed methods which may address this limitation for liquid composite moulding technologies: In-Mould Gel-Coating (IMGC) using a separator fabric [4], and In Mould Surfacing (IMS) with a silicone shim [5]. Di Tomasso et al. [6] reported ranges for styrene time-weighted average (TWA) concentrations to be 28-70 ppm for the open mould gel-coating process and 0.23–0.37 ppm for the IMGC and IMS closed mould technologies studied in this paper. The new processes reduce average styrene emission levels by over 98% with obvious benefits for worker health and the reduction of environmental burdens. The two methods are discussed below.

1.1 In-Mould Gel-Coating (IMGC)

The alternative to open-tool gel-coating is to mould the laminate in a closed mould tool then slightly open the mould to create space where the gel-coat can be injected. The mould-opening technique is adequate for flat mouldings but requires complex tooling for 3D components if a uniform gel-coat thickness is to be achieved. The initial concept for an

IMGC process was to develop a spacer/barrier fabric (separator layer) to create a permeable void space adjacent to the mould tool surface into which gel-coat could be injected whilst keeping the laminate and gel-coat resins apart. This technique allows complete manufacture of a composite component in a closed mould tool system, thus minimising styrene emissions, and provides a controlled thickness gel-coat surface which sensibly conforms to the tool face topology. The concept is applicable to all Liquid Composite Moulding (LCM) processes, especially Resin Transfer Moulding (RTM) and Resin Infusion under Flexible Tooling (RIFT, a.k.a. SCRIMP™ or VARTM). Automation of gel-coat application could deskill the process and improve repeatability of gel-coating.

The tri-laminate separator layer systems tested to date have proven to be the weak link when testing gel-coat-to-laminate adhesion strength. All components of the system should be unaffected (e.g. not swollen or dissolved) by the resin system in use. The tri-laminate must be achieved within an economic framework that allows the technology to compete with current low-skill processes until the legislative framework forces changes in the industry. The tri-laminate challenge for advanced textile processes is to generate a conformable, chemically stable, tri-layer spacer fabric with good mechanical integrity (adhesion between layers and cohesion within layers). The use of a separation layer could permit infusion of incompatible laminate and coating resins. Mechanical interlocking of the matrix and gelcoat by the separator layer could ensure greater adhesion. This could allow phenolic coatings for fire resistance, or poly/vinyl-ester coatings for good cosmetic finish, on any laminate resin system. The optimum separator layer has not yet been identified. Failure may occur where the separator layer joins to either the gelcoat or the laminate or there may be cohesive failure within the spacer/barrier fabric. The material combinations studied to date may limit the wider application of the technology. The merits and disadvantages of IMGC relative to hand lay-up are summarised in Table 1.

1.2 In-Mould Surfacing Technology (IMS)

An alternative approach investigated was the IMS technology patented by Alan Harper Composites (AHC) [5]. This uses a removable, preferably reusable, low adhesion elastomeric (silicone or similar) shim in the mould tool during lamination to define the space that will become the gel-coat layer. After laminating the component with the shim in place in the mould, the mould is opened at the appropriate degree of cure to remove the shim while the component remains attached to the counterface of the mould, then the mould is closed before gel-coat is introduced into the remaining space. The merits and disadvantages of IMS relative to hand lay-up are summarised in Table 1.

This paper considers both the IMGC and IMS technologies as potentially viable routes to closed mould gel-coating processes. Key performance indicators (surface quality and pull-off adhesion tests) are measured and referenced to values from conventional hand painted gel-coat techniques. Surface quality is often measured to quantify gloss, waviness and print-through [7-9] with the automotive industry using goniophotometry [10], ASTM E430–11 and Wave-Scan instruments [11-13]. It is essential for the composites producers in the European Union to be ready for any impending changes to permitted styrene levels arising from the Registration, Evaluation, Authorisation and restriction of CHemicals (REACH) regulations. As Robertson [14] drawing on Willard [15] and Doppelt [16], wrote "[p]reparing in a proactive orderly way is almost always more cost-effective than having to respond reactively to a changing regulatory environment".

2. Experiments

2.1 Materials

The materials used during the experiments are described below. For mould release Loctite Frekote 770-NC semi-permanent mould release (batch LN2CAA9290 1632) and Meguiar's Mirror Glaze no. 8 wax M-0811 were used. DeIjssel (Moordrecht, NL) 'special VI ISO' white pigmented polyester gel-coat (manufacturer data sheet; 600 mPa.s viscosity; experimental measurements: 46.4 ± 11.1 MPa tensile strength, 3.9 ± 0.3 GPa tensile modulus, 1.4 ± 0.4 % elongation at break, tested according to EN ISO 527-2 after 16 hours cure at 40°C then post-cure for 4 hours at 80°C) with 2% Butanox M-50, methyl-ethyl ketone peroxide (MEKP) catalyst; DSM Synolite 1967-N-1 unsaturated DCPD-based polyester resin (manufacturer data sheet for resin cured with 1.5% NL49P accelerator + 1% Butanox M-50 MEKP catalyst, cure for 24 hours at room temperature followed by 24 hours post-cure at 70°C: 160-180 mPa.s initial viscosity, 70 MPa tensile strength, 3.8 GPa tensile modulus, 2.3% elongation at break, according to EN ISO 527-2) with 1.5% Butanox M-50 MEKP catalyst and Scott Bader Accelerator G (1% solution of cobalt soap dissolved in styrene) were used. The reinforcement was 300 gsm Saint Gobain Vetrotex Unifilo U850 random swirl glass fibres. Baltex (Ilkeston, UK) and CentroCot (Busto Arsizio, Italy) supplied tri-laminate fabrics as separator layers. They consist of polyester (PET) knitted fabrics adhesively bonded on both sides of 50 μm impermeable polyurethane (PU) film. For RTM/IMS technology, a sprayed addition-polymerisation silicone shim membrane defines the gel-coat volume (Alan Harper Composites Ltd (AHC)). Spabond (Gurit, UK) 340LV epoxy adhesive system with fast hardener was used to prepare the pull-off adhesion test samples. For better comparison of the results commercial components were also used. Their characteristics are summarised in Appendix A.

2.2 Sample manufacturing process

To sensibly simulate the RTM process and allow appropriate in-mould gel-coating experiments to be undertaken, a Double-Glass-Plate-Mould (DGPM) was used (Fig. 1) to permit full visibility of both the gel-coat and resin flow into the cavity in order to better understand the process. The DGPM has two 300 square x 19 mm thick plates of glass (to withstand injection pressures) each with a central injection point to allow injection of gel-coat or laminate resin to the respective sides of the separator fabric. The glass plates are held a set distance apart by four stainless steel shims creating a 4 mm cavity in which the laminate complete with gel-coat is produced. Neoprene inner (∅ 8 mm) and outer (∅ 6 mm) frame seals were coated with mirror glaze wax to prevent bonding to the cured laminate. The first halves of each of the inner and outer frame seals were placed against one side of the mould in the correct position. Breather cloth was placed between the frame seal and the mould tool face at all four corners to create vent paths. The four shims were placed in the space between the inner and outer seals at the four corners of the mould. The two glass plates (with four-layer fibre-pack, sealants, separator fabric, shims etc. between them) were placed inside the clamping frames with four M12 bolts used to pull the two halves together. A ratchet torque wrench was used when clamping the mould to ensure the cavity height was equal at all four corners. Both resin and gel-coat were injected using BD Plastipak 100 ml capacity syringes at ambient temperature with only positive pressure and with a one hour interval for one resin to gel before the other resin was injected.

For sample preparation, three different methods were applied: (a) conventional hand-painted gel-coat (CHP), (b) In-Mould Gel-Coating (IMGC) process with trilayer separator fabric to isolate the resin and gel-coat sides, and (c) In-Mould Surfacing (IMS) technology using silicone shim to form the cavity prior to subsequent gel-coat injection. In every case, the DSM polyester resin and the DeIjssel gel-coat were used as laminate resin and gel-coat respectively to prepare the flat composite test panels. The ambient conditions were 23±2°C temperature, 45±10% relative humidity and 1020±10 mbar atmospheric pressure. After sample preparation, all laminates were cured at 40°C for 16 h before an 80°C post-cure for 4 h to ensure full cure of the composite samples before the mould was opened. A 20°C/hour ramp rate was used in all cases.

Hand-painted ~200 mm square flat panels were produced by applying and gelling (one hour dwell time) the coating on a glass plate before the four layer Unifilo glass reinforcement laminate was manufactured by resin infusion under flexible tooling with a flow medium (RIFT II) [17] at ~15 mbar absolute pressure.

For the IMGC samples, a 320 mm square separator fabric was draped over the fibre pack and frame seals and the second set of inner and outer frame seals placed above the separator fabric in the DGPM tool. This inner frame seal would define the gel-coat cavity with the outer frame seal being the secondary sealing arrangement. The gel-coat was injected with one hour dwell time before the laminate resin was introduced.

In-Mould-Surfacing (IMS) samples were also made in the DGPM. For IMS, only the outer frame seals were used and a 210 mm square 1 mm thick silicone shim (previously made between two shimmed glass plates) was placed into the mould tool before the glass reinforcement. The fibre pack was then cut to 190 mm square and placed inside the outer frame seal with a 5 mm peripheral gap. Laminate resin was injected first, allowed to cure for one hour, then the silicone shim was removed, breather cloths placed into each corner for venting and gel-coat was injected with a second syringe.

2.3. Surface measurements

The surface quality of the samples was monitored using a Qualitest Wave-Scan Dual device (Model GB-4840, serial number 1062212) and 100 mm scan length. The parameters selected were: dullness (du), structure spectrum at different representative wavelength ranges (Wa, Wb, Wc, Wd and We), shortwave (SW), longwave (LW) and distinctness of image (DOI) according to ASTM E430-11 [18]. Low dullness (du) and low spectrum (Wa…We) indicate a high gloss surface. For example, du < 40 means a high gloss surface while du in the range 40-65 represents “semi-gloss to high gloss”. When the DOI is high, the surface is smoother and much glossier. The maximum (best) value of DOI is 96.

2.4 Cross-section analysis

The composite samples were mounted in potting resin (Stuers Epofix resin with hardener) and cured for 24 h at room temperature. The samples were then ground and polished (Buehler Metpol 2000 grinder/polisher machine) and analysed using an optical microscope (Olympus BX60M) with Stream Motion software.

2.5 Pull-off adhesion tests

Pull-off tests were carried out according to EN ISO 4624:2002 [19] to characterise the adhesion between the gel-coat and the substrate. Two target levels were set for pull-off adhesion strength: a minimum value of 8 MPa for low-performance situations, and a target of 20 MPa for components subjected to high stresses. For each sample, square plates of minimum 30 mm edge were cut with a diamond blade. Six specimens were used for each sample set. Both sides of the specimens were roughened with P80 (grit size of 200 μm) sandpaper for increased mechanical keying of the adhesive. Aluminium faced cylindrical test “dollies” were prepared with a nominal diameter of 20 mm on one side and M10 thread on the other side. The dollies faces were machined perpendicular to their principal axis and were sand blasted in a Guyson Super 6 Blastcleaner Cabinet (serial no. 68668) with alumina blast abrasive media (Guyson NFK 100 Brown Saftigrit CSS12 issue 8) immediately before bonding to minimise contamination of the surface. The region outside the intended bonding area was temporarily protected using masking tape. The aluminium test dollies were fixed into a centring device with three M8 bolts to ensure proper coaxial alignment during bonding with the epoxy adhesive system. The samples were post cured at 70°C for 5 hours before the pull-off test. The cured adhesive and gel-coat on the test specimens was cut through to the substrate around the circumference of the dollies using a DeFelsko PosiTest Pull-Off Adhesion Tester cutting tool with 20 mm inner diameter [20]. The dollies were extended using a 60 mm long and 16 mm diameter steel adapter with M10 metric internal thread on both sides which can then be easily installed in Instron type 500.625 M2 16 grips for the pull-off test permitting a longer gripping surface. An Instron universal test frame (system ID: 5582J7466, S1-16754) with a ±100 kN load cell (cat.no. 2525-801, ser.no. UK195) was used for the measurements. To comply with the ISO 4624:2002 test standard, failure should occur within 90 s. A 1 N preload and a 60±1 mm gap between the grip faces were set. The test speed was 1 mm/min.

3. Results and discussion

3.1 Surface measurement results

Six Wave-Scan measurements were made along two orthogonal directions for every sample. For the orthotropic IMGC samples, the test directions were aligned with the wale/course respectively. The data are summarised in Table 2 and plotted in Fig. 2. All the mean values of the spectrum parameters were below 10 indicating that the surfaces have high gloss. In some small areas of the hand painted samples, there were minor patches of fibre print-through. The commercial parts had a wide range of surface quality. The boat sections and car panels had high gloss surface in overall (Wave-Scan values are less than 30). The highest surface quality was for Boat 1 sample with the values are less than 3. The bridge components were quite dull (Wave-Scan values between 30 and 80). These differences can be explained by the various requirements of these sectors.

3.2 Cross-section analysis results

The cross-sections of the samples were analysed as well as the thicknesses of the different layers. Fig. 3 shows cross-sections for hand painted, IMS, IMGC (T6, NT1 and NT2 trilayers) samples with the data in Table 3. The low coefficient of variation (CoV) for IMS panels was a result of the accurate thickness of the silicone shim used to define the cavity before gel-coat was injected. The NT1 fabrics had large intratow voids in the composites and consequent lower pull-off strength. The hand-painted and IMS samples both had no evidence of intratow voids with improved adhesion between the gel-coat and glass reinforced polyester. The hand-painted samples had an intimate connection between the laminate and gel-coat resins with some glass fibres partially embedded in the gel-coat which may improve the adhesion. The glass fibres of IMS samples were all embedded in the laminate resin. The topology of the reinforcement is reflected in the form of the gel-coat to laminate interface, but not at the cosmetic external surface

3.3 Pull-off adhesion tests results

The tests were conducted with great care to avoid off-axis stresses and thus minimise early cleavage and/or peel failure. A deeper understanding of the interactions between the different layers of the composite would require *in situ* strain/stress measurement which is a non-trivial issue given the sample dimensions (63 mm perimeter by 3 to 4.5 mm thick) and the presence of the individual sub-layers presented edge-on during testing. The pull-off test results of flat panels from the hand painted gel-coat, IMGC (T6, NT1 and NT2) and IMS are summarised in Table 3, while the possible failure modes are classified in Fig. 4.

The hand painted gel-coat samples were used as a reference. They all failed within the composite structural laminate (Fig. 5a) in the same way as the commercial components used for comparison (Mode D). Almost the complete surface of the glass fibres became white after the test showing the resin was cracking from the fibres during the fracture. It underpins the good surface adhesion between the gel-coat and the composite part because the fibres are both embedded in the resin and the gel-coat (see the cross-sectional image of Fig. 3a).

The failure mode was delamination (Mode C) within the trilayer in all cases for the IMGC technology, which is completely different from the hand painted samples. The pull-off strength of IMGC T6 was nearly 70% above the lower target 8 MPa level and almost double the results from previous tests with prototype separator layers [21]. However, this effect could also occur due to the change from Crystic to DSM resin. The pull-off strengths for the optimised separator fabrics (NT1 and NT2) with IMGC technique were 10-20% below the 8 MPa target attributed to the intratow voids either side of the separator fabrics. The separator layers used to date are the weakest link in the load chain and have relied on a bonded three-layer structure. This effect can be seen in Fig. 5b and c on the test samples after pull-off test, where the impermeable film was completely removed from the surface. There is scope for the development of integrated stronger separator systems with fibre continuity between the two faces and a membrane with no or very limited permeability to liquid resins at mid-thickness. This might be achieved by stitching/tufting through a polymer film but the film would need to close around the fibre-filled hole and the film would also require good tear resistance. Another alternative might be a polymer film with re-entrant features (e.g. hooks or mushrooms) to facilitate mechanical keying between the respective resins and the film. To date, suppliers for such alternative materials with compatibility in the resin systems under consideration have not been identified.

For the IMS technology, pull-off strengths achieved the higher 20 MPa target and the mean value fell just 10% short of that for the hand painted samples with the same resin and gel-coat system. This difference can be explained by the lower amount of fibres that took part in the load transfer during the pull-off test; see the resin failure parts in Fig. 5d, which is the result of the slightly uneven gel-coat line in Fig. 3b. The failure mode was cohesive fracture within the composite structural laminate (Mode D). However, the adoption of any silicone technology will not be readily implemented for high-performance composite industries due to the potential for silicone transfer that may compromise subsequent adhesive bonding (or painting). Further, while the membranes are reusable, they currently do have a finite lifetime of the order of tens of cycles dependent on the resin system in use.

Figure 6 shows the pull-off adhesion strengths for the above samples referenced to measurements from a variety of commercial mouldings sourced from both within and outside the consortium and from an earlier TSB-funded Zero Emission Enterprises (ZEE) project [22].

4. Conclusions

The two different approaches both offer significant reductions in styrene levels in the workplace [4]. The gel-coating of the hand-painted flat panels, the IMGC and the IMS panels gave complete surfaces with just minor imperfections reflecting the topology of the moulding glass plates. In all cases, the Wave-Scan results for the flat panels indicated high gloss surfaces.

The more promising environmental benefits of the IMGC technology are compromised by the fragile structure of the separator layers available to date. The technology suffers from poor pull-off strength due to delamination within the separator layer, albeit that the trilayer fabrics used in InGeCt project had double the strength of fabrics from the earlier ZEE project. This issue may be mitigated by integrated stronger separator systems but such alternative materials have not been identified yet. The IMS technology resulted in cohesive failure in the laminate and the results were just 10% short of that for the hand painted samples, but the industry perception of silicone contamination and styrene release during shim removal remain as issues. However, the new processes offer a comparable surface and adhesive pull-off properties to the tested commercial samples.

The future research challenge is to design a separator layer with improved mechanical integrity and then to develop the layer further to enhance conformability to three-dimensional topology complex composite surfaces. There is scope for further optimisation of the process, and to address the issues in Table 1.

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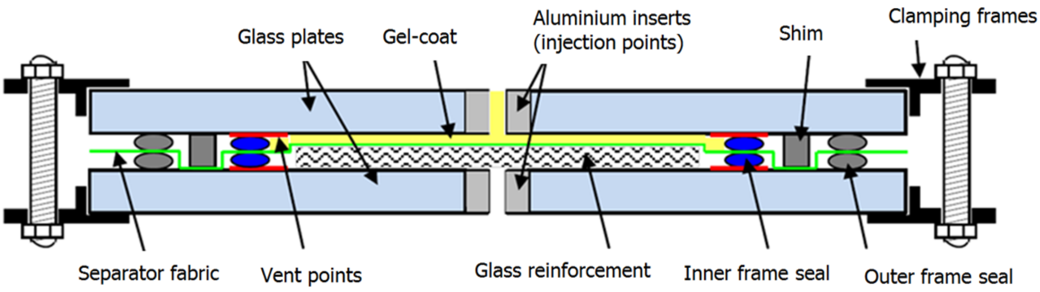


(a)

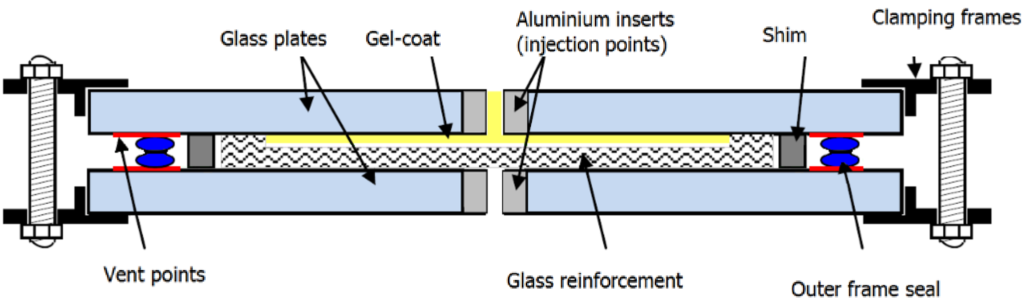
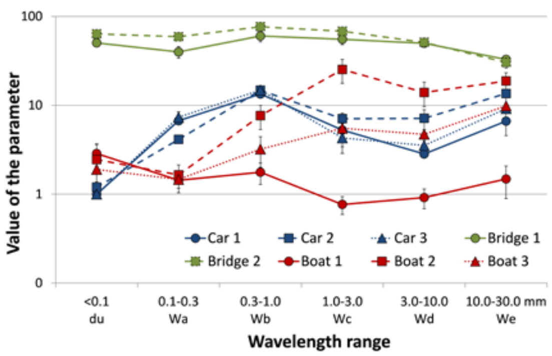
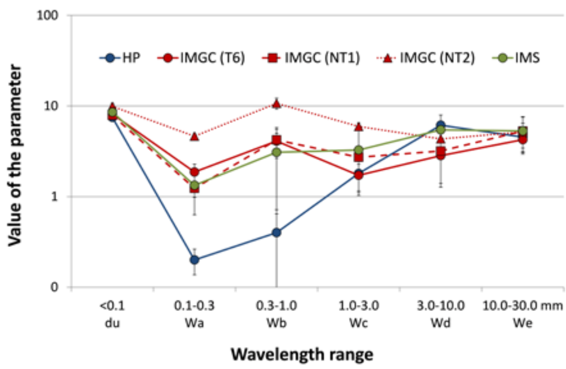


Fig. 1. Cross section view of DGPM arrangement during IMGC (a) and IMS (b) technique





(a) (b)

Fig. 2. Wave-Scan measuring results for commercial (a) and test samples (b); HP – hand painted, IMGC – In-Mould Gel-Coated, IMS – In Mould Surfacing samples

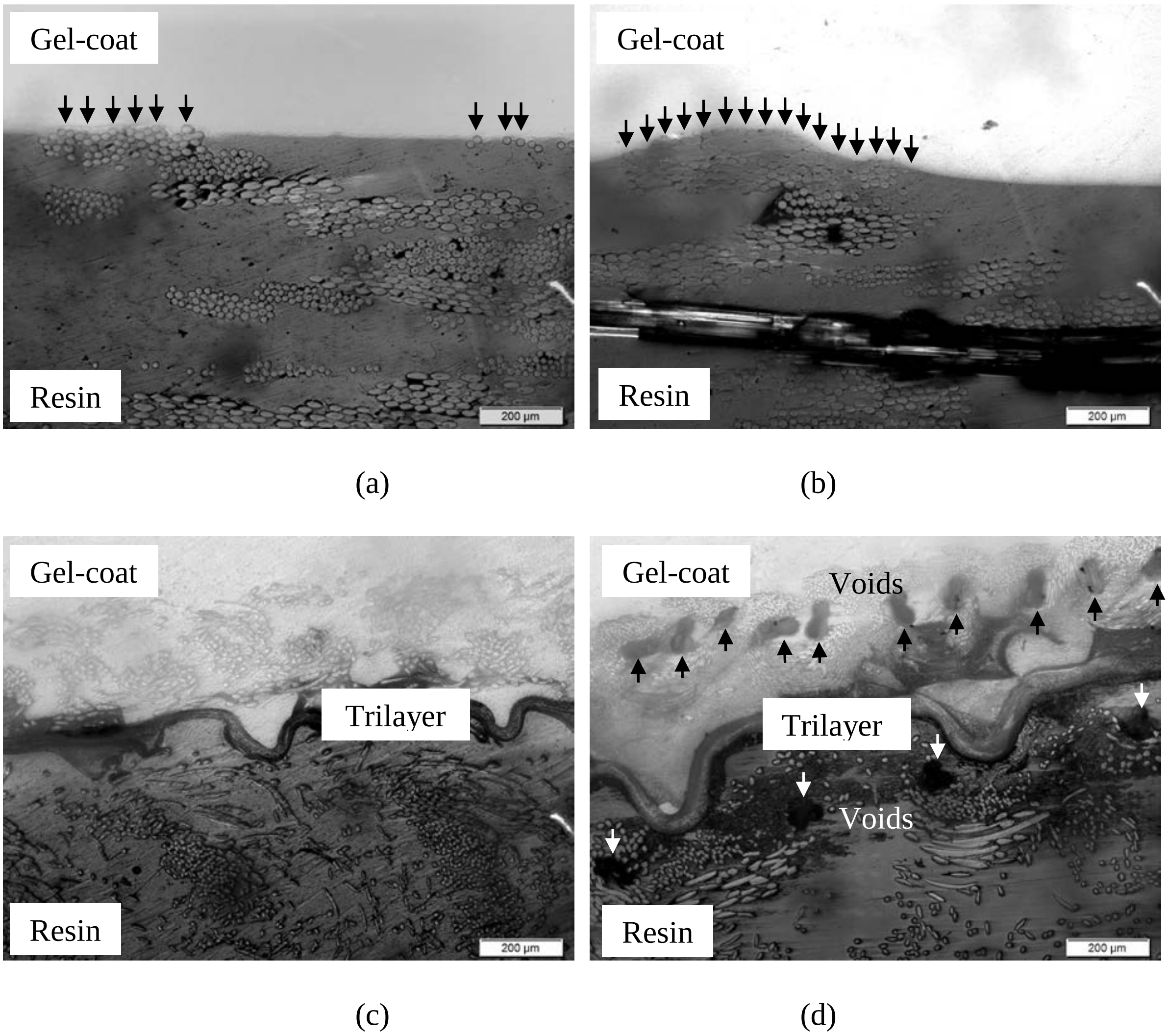
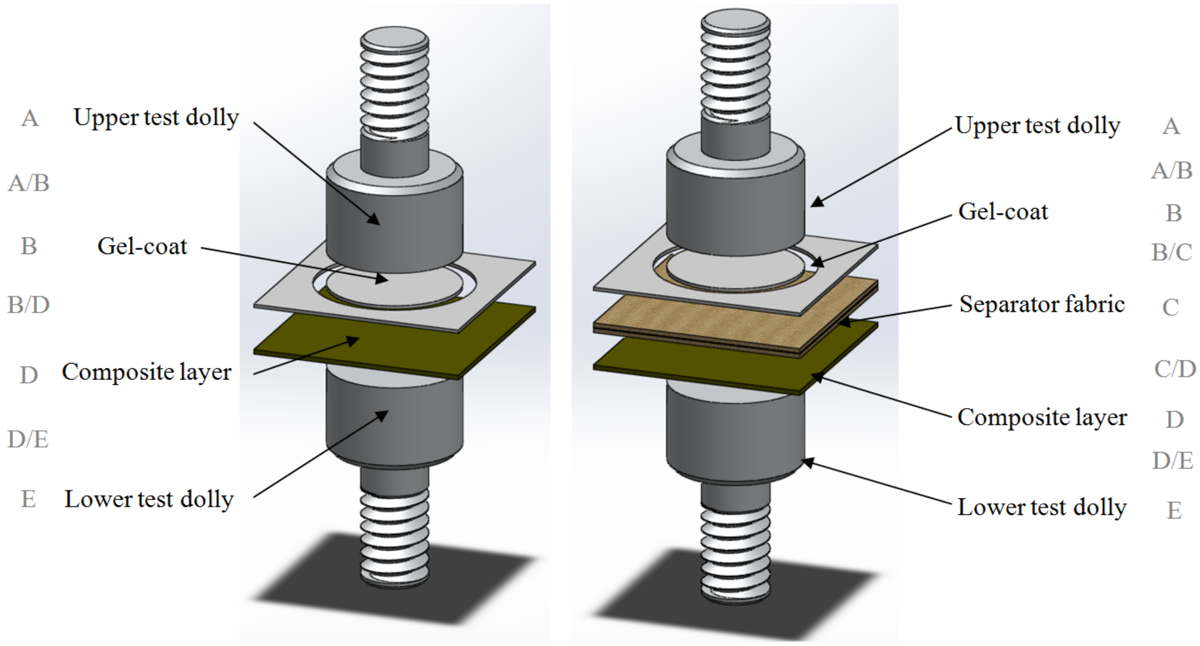
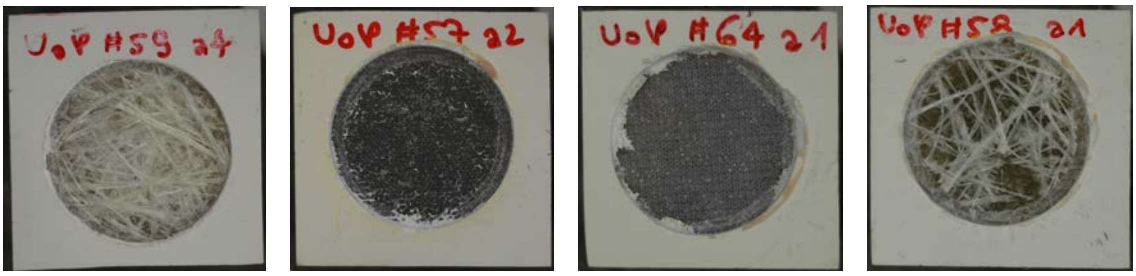


Fig. 3. Cross-sections of (a) hand painted (UoP#59), (b) IMS (UoP#58), and IMGC (c) T6:UoP#57 and (d) NT1:UoP#64 samples



(a) (b)

Fig. 4. Representation of the pull-off test specimen layers without (a) and with (b) separator fabric and their failure modes as follows: A - cohesive failure of upper test dolly (did not occur), A/B - adhesive failure between upper test dolly and gel-coat,
B - cohesive failure of gel-coat, B/C - adhesive failure between gel-coat and separator fabric (delamination), B/D - adhesive failure between gel-coat and composite laminate (delamination), C - failure of separator fabric (e.g. delamination within the layers), C/D - adhesive failure between separator fabric and composite laminate, D - cohesive failure of composite laminate,
D/E - adhesive failure between composite laminate and lower test dolly, E - a cohesive failure of lower test dolly (did not occur)



(a) (b) (c) (d)

Fig. 5. Representative failed surfaces of the hand painted (a), IMGC with T6 (b) and NT1 (c) separator fabrics and IMS technology (d) samples after pull-off test

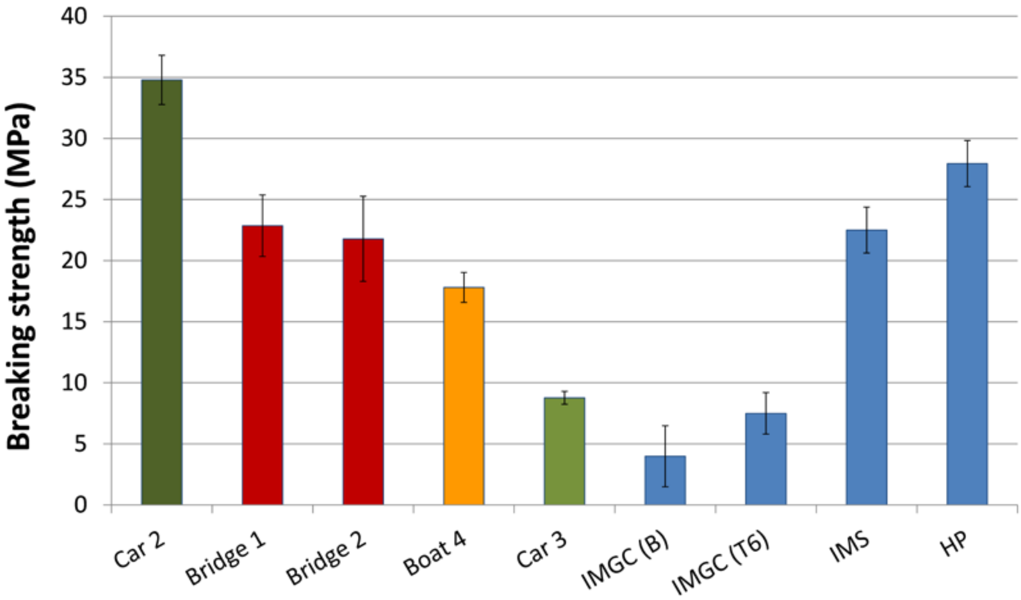


Fig. 6. Pull-off strengths for gel-coat to structural laminate for a variety of commercial moulding and for the plates manufactured in this research. The different colours indicate different resin systems. HP – hand painted, IMGC (B) and IMGC (T6) – In-Mould Gel-Coated samples with Baltex and CentroCot trilayer #6 separator fabrics respectively, and IMS – In Mould Surfacing sample

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Table 1
The relative merits and disadvantages of IMS and IMGC relative to hand lay-up

IMGC	IMS
Advantages • More controlled process for lay-up and gel-coat thickness control. • Faster gel-coating time. • Reduced gel-coat thickness relative to HLU • Minimal styrene emissions throughout the process. • May be one of a limited number of choices if occupational exposure levels for styrene are reduced. • Incompatible laminate and gel-coat resins easily implemented. • Possibility of simultaneous gel-coat and laminate resin injection subject to appropriate control systems.	Advantages • More controlled process for lay-up and gel-coat thickness control. • Faster gel-coating time. • Reduced variation in gel-coat thickness. • Gel-coat thickness determined by chosen shim. • Minimal styrene emissions, except while removing shim. • May be one of a limited number of choices if occupational exposure levels for styrene are reduced. • Shim may be ~€20/m^2 with potential for >10 product cycles/shim
Disadvantages • Collapse of the separator layer under consolidation pressure leading to reduced permeability and inhibiting the flow of gel-coat. • Print-through of fibres in the separator layer, or close to the gel-coat surface, affecting surface finish and compromising customer acceptance, service, durability and repair, • Potential for wicking of moisture through the fabric, particularly over extended timescales. • Separator layer drape/conformability may be limited for complex three-dimensional tools • Folds, wrinkles and joints where components exceed standard fabric roll widths. • Sharp corners in the tool could pierce the separator layer. • Reduced permeability to the resin system adjacent to 3D features in the mould. • New technology without service history biasing clients against adoption. • Additional costs may be unacceptable to industry until driven by changes in VOC regulations. • Development separator fabrics are likely to cost >€5/m^2 in production	Disadvantages • Styrene emissions to the workplace when the mould tool is opened to remove the shim. • Silicone transfer to the mould and component surfaces with the potential for weak interfaces where subsequent bonding (or painting) are required. • Control of part alignment on very large structures (boat hulls or wind turbines) especially if the component separates from the mould during shim removal. • Shim handling and consequent labour requirements. • Potential for sagging issues dependent on mould geometries. • Limited options for different chemistry in the gelcoat and the laminate resins. • Limited durability of the shim over repeated process cycles • Scalability of the process for very large components. • Additional costs may be unacceptable to industry until driven by changes in VOC regulations.

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Table 2
Wave-Scan measuring results

	Wavelength ranges	**Hand painted**	**IMGC technology**			**IMS technology**
			T6	**NT1**	**NT2**	
du	<0.1 mm	7.4±3.4	8.0±0.5	8.5±0.8	9.9±0.5	8.7±0.6
Wa	0.1 – 0.3 mm	0.3±0.3	1.5±0.5	1.4±0.6	4.1±0.6	1.4±0.9
Wb	0.3 – 1 mm	0.6±0.3	3.2±1.2	3.4±1.8	9.5±1.7	3.4±2.4
Wc	1 – 3 mm	1.2±1.0	1.9±0.7	2.8±1.9	5.5±0.8	4.4±2.1
Wd	3 – 10 mm	4.4±1.8	3.1±1.3	3.5±1.8	5.1±1.3	7.0±2.5
We	10 – 30 mm	3.7±1.8	5.0±1.3	6.0±2.0	5.5±1.6	6.0±2.0
SW	0.3 – 1.2 mm	0.5±0.3	2.3±1.0	2.7±1.6	8.6±0.6	2.9±2.1
LW	1.2 – 12 mm	0.9±5.0	0.8±0.4	1.2±1.0	2.0±1.5	2.1±0.9
DOI range = 0–96		93.9±0.1	93.4±0.2	92.2±0.3	92.0±0.3	92.8±0.3

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Table 3

Pull-off adhesion properties for experimental and commercial samples

	Hand painted	IMGC technology			IMS technology	Commercial components				
		T6	NT1	NT2						
Plate ID	**UoP#59**	**UoP#57**	**UoP#64**	**UoP#67**	**UoP#58**	**Car 3**	**Car 2**	**Bridge 1**	**Bridge 2**	**Boat 4**
Composite thickness (mm)	2.97±0.28	4.08±0.04	4.29±0.02	4.21±0.04	3.64±0.03	0.97±0.02	2.89±0.02	3.66±0.10	3.73±0.15	2.77±0.15
Gel-coat thickness (mm) CoV	0.66±0.16 (24%)	1.25±0.17* (14%)	1.63±0.20* (12%)	1.36±0.30* (22%)	1.07±0.03 (3%)	0.05±0.01 (20%)	0.21±0.01 (5%)	0.26±0.03 (11%)	0.26±0.04 (15%)	0.37±0.07 (18%)
Breaking strength (MPa)	21.73±1.55	13.30±0.44	6.65±0.28	7.33±0.53	19.75±0.53	8.77±0.52	34.79±2.01	22.61±2.38	21.78±3.48	17.80±1.22
Typical failure mode	D	C	C	C	D	D	D	D	D	D

*IMGC technology gel-coat thickness includes the gel-coat side of the trilayers

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Figure Captions

Fig. 1. Cross section view of DGPM arrangement during IMGC (a) and IMS (b) technique

Fig. 2. Wave-Scan measuring results of flat panels made by different processes at vertical/wale (a) and horizontal/course (b) directions

Fig. 3. Cross-section of hand painted, IMS, IMGC samples and the separator fabric embedded into composite structure

Fig. 4. Representation of the pull-off test specimen layers without (a) and with (b) separator fabric and their failure modes

Fig. 5. Representative failed surfaces of the hand painted (a), IMGC with T6 (b) and NT1 (c) separator fabrics and IMS technology (d) samples after pull-off test

Fig. 6. Pull-off strengths for gel-coat to structural laminate for a variety of commercial moulding and for the plates manufactured in this research. The different colours indicate different resin systems.

Tables

Table 1 The relative merits and disadvantages of IMS and IMGC relative to hand lay-up

Table 2 Wave-Scan measuring results of flat panels

Table 3 Pull-off adhesion properties for experimental and commercial samples

Appendix A Characteristics of the commercial panels

Component	**Characteristics of the lay-up**
Bridge 1	gel-coat; QI non-crimp fabric (4x1200 gsm) infused directly on the partially cured gel-coat on the same day and demoulded next day (composite tooling).
Bridge 2	gel-coat; QI non-crimp fabric (4x1200 gsm) infused directly on the partially cured gel-coat (same day) and demoulded next day (coated steel tooling).*
Boat 1	gel-coat; barrier coat, hand laminated CSM layer; infused laminate of honeycomb structured surfacing veil (2 mm); non-crimp fabric (6x1200 gsm).*
Boat 2	gel-coat; infused laminate of honeycomb structured surfacing veil (2 mm); glass fabric (200 gsm); 10 mm PVC core; glass fabric.*
Boat 3	gel-coat; barrier coat; infused laminate of honeycomb structured surfacing veil (2 mm); glass fabric (200 gsm); PVC core (10 mm); glass fabric.
Boat 4	gel-coat; CSM (300 gsm); QD glass (2x1200 gsm); PVC core (35 mm); QD (2x1200 gsm).**
Car 1	paint on A-saloon front wing reverse engineering suggested 46% fibre volume faction, carbon fibre lay-up [+45/-45/90/Ō $]_s$
Car 2	paint on CFRP C-sports car panel***
Car 3	paint on GFRP M-sports car panel***

* samples were not tested by pull-off due to the failure of barrier coat or surface veil

** PVC core and non-gel-coated laminate were removed prior to pull-off test

*** car panel information is commercial-in-confidence