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Optimization of RTM processing parameters for Class A surface finish

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ABSTRACT

Resin transfer moulding (RTM) has the potential to become an efficient and economical process for manufacturing large automotive composite parts. For body panels, the material and processing parameters must be optimized in order to achieve a Class A surface finish. In this work, the Taguchi method was used to investigate the effect of low profile additives, injection pressure, temperature gradient, filler content, styrene content and gel time on the surface finish of glass fibre polyester composite panels. The low profile additives (LPA) concentration, mixed in with the resin to compensate for its chemical shrinkage, was found to be the most influential parameter affecting surface roughness and waviness. More samples were subsequently moulded under the corresponding optimum processing conditions for validation and variability assessment.

1. Introduction

The automotive industry is seen as one of the major potential users of advanced composite materials in the future. This industry is increasingly using resin transfer moulding (RTM) to produce composite body panels at high volumes and low costs. However, one of the recurring issues is the control of the parts' surface finish. This is partly due to the difficulties related with process optimization, which requires an appropriate resin formulation for short cycle times, mould design and proper moulding parameters selection. It is therefore difficult to achieve Class A surface quality according to the industry specifications and standards. In practice, Class A surface finish refers to a perfectly polished, high luster surface which is free of porosity and scratches of any kind [1–3]. Consequently, a standard method for Class A surface finish measurement has never been developed for composites. Typical surface roughness measurement systems used in the automotive sector are quality measurement system (QMS), BYK wave-scan, D-sight and the ONDULO quality control systems [4]. The main drawback of all these techniques is that they can only be used with a high level of gloss, which is absent in most composite surfaces [5]. However, Debolt [5] described a procedure to quantify surface roughness for Class A finish with a non-contact profilometer. This procedure employed band-pass filtering and Fourier transforms for extracting regions of particular wavelengths. This method was found to be very efficient in quantifying the differences in plates moulded under varying processing conditions.

Low profile additives (LPA) are thermoplastic additives mixed in with unsaturated polyester (UP) and vinyl ester resins to compensate for the cure shrinkage. Lucas et al. studied the effects of LPA and filler on polymerization reaction, mechanical properties and surface rugosities [6]. Without the addition of LPA, the average roughness R_a was measured to be 0.29 μm. For polyvinyl acetate (PVAc) concentrations that resulted in shrinkage compensation, the measurements were reported around R_a = 0.06–0.08 μm and a critical concentration (8%) of LPA was needed for shrinkage compensation. The effect of LPA content and other process parameters on pressure variations during RTM manufacturing were investigated using design-of-experiments [7]. A significant pressure increase was observed in the later stages of cure due to the LPA content in the resin. An optimum LPA concentration of 10% was found to lead to the maximum pressure increase, which confirmed the results observed in [8]. Kim et al. found that a satin weave on the outside of the mat gave the best finish [9]. Matthews et al. used statistical experimental design (SED) techniques to study the effect of various parameters on the degree of surface finish [10]. This research established that gloss increased with the lower filler content, fibre volume fraction (V_f), mould temperature and higher injection pressure, whereas roughness reduced with higher filler content, injection pressure and with lower V_f and mould temperature. This work was further verified by Bayldon [11]. Higher filler content and injection pressures were confirmed to result in better surface finish. The effect of LPA content (between 0% and 40%) on cure kinetics, cure shrinkage, gel time, viscosity variations and morphological changes in Scott Bader PD9551 unsaturated polyester resin used in this research were studied and have been discussed in detail in [8]. A critical LPA amount of 10% was found for complete shrinkage compensation. A model for the resin shrinkage as a function of degree-of-cure was proposed.

Karbhari et al. [12] studied the effect of material and process variables on the mechanical performance of RTM moulded parts

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using experimental design based on the Taguchi method. This method was found to be efficient and economical to evaluate the relative importance and interaction of both process and performance related parameters. The Taguchi method has also been applied successfully in various other fields of study [13–20]. Regression analysis is also one of the most widely used statistical tools because it provides simple methods for establishing functional relationship among variables. It can be employed to develop a suitable model for predicting dependent variables from a set of independent variables.

In this work, a UP resin and fibreglass preforms were used to mould a series of plates by RTM. A selection of material and processing parameters identified in a previous study [7,8]; LPA, styrene and filler content; gel time, temperature gradient and injection pressure, were investigated. The main objective was to find a set of optimum parameters leading to the best surface quality of the panels using a design of experiments (DOE) developed with the Taguchi method. Analysis of variance (ANOVA) and multiple regression analyses were carried out on the measured surface roughness and an empirical model was derived. The manufacturing of a second series of plates was then conducted to validate the model and measure the process variability.

2. Materials and experimental procedures

Polyester resin PD9551 from Scott Bader Company Ltd. was used in this research. The LPA added to the resin was the PD9419 polymer solution from Scott Bader, containing two types of additives: polyvinyl acetate (PVAc) and polymethyl methacrylate (PMMA). BLR®2 calcium carbonate filler (30%), from OMYA, *tert*-butyl peroxybenzoate catalyst (2.6% of Trigonox® 93), from Akzo Chemicals, and cobalt 2-ethylhexonoate accelerator (0.5%), from Akzo Chemicals, were used. The F3P fibreglass preforms, provided by Ford Motors Co., contained 35% fibre fraction by weight and were made of chopped fibre bundles with a surface veil on top and bottom made of thin continuous fibres. The surface with the lowest binder concentration, referred to as Side-A, was considered for the surface quality measurements.

2.1. RTM setup and test matrix

Composite test samples, 24 cm by 26 cm, were manufactured using a heated steel mould mounted on a hydraulic press. The mould had a mirror-like polished finish and it was measured with a Mitutoyo Surftest 401 Portable Surface Roughness Tester. The driving speed of this profilometer was 0.5 mm/s and the sampling rate was 400 points/s. The diamond stylus had a radius of 5 μm. Several scans were taken on the smoothest region of the mould and for a cutoff wavelength of 2.5 mm, the average roughness R_a ranged from 0.5 μm to 0.7 μm. The surface roughness of moulded plates was measured with the same profilometer as a means of comparison. Their average roughness ranged from 0.3 μm to 0.6 μm, which shows that this setup produces parts with an excellent surface quality. The mould was instrumented with type J thermocouples and Dynisco PT422 pressure sensors connected to a Vishay's System 6000 data acquisition system. The mould platens were heated to the required temperatures with a Conair circulating water heating system. The resin at room temperature was injected into the mould cavity with a Radius Engineering constant pressure pneumatic-controlled injector. The 3.175 mm thick picture frame was sealed using a Gore-Tex joint sealant gasket. The bottom mould was kept at 90 °C and top mould was heated at different temperatures based on the required gradient. The preform was cut and placed inside the mould just before injection. Side-A of the preform was placed towards the hottest mould platen. The injection and vent ports were designed to create a uniform linear flow front though the fibre preform. The mould pressure sensors locations are shown in Fig. 1 and PS4 was mounted on the injection pump to measure injection pressure. The mould surfaces were cleaned with acetone and coated with a single layer of Chemlease 41–90 mould release agent before each injection. After the injection, the vent port was closed with locking pliers and the injection pressure at the pump and the gate was kept constant. Manufactured composite panels were kept inside the mould until the resin achieved the maximum pressure level at the end of the polymerization.

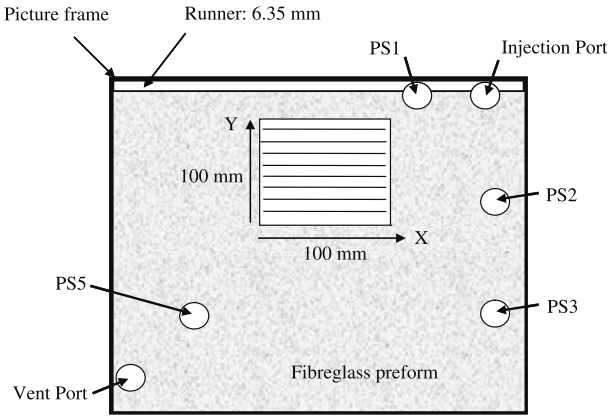

Fig. 1. Location of the roughness measurement area and position of the pressure sensors on the moulded sample.

In this study, a test matrix of eighteen trials (L_{18}) with six parameters (LPA, styrene, filler, gel time, injection pressure, and temperature gradient), at three levels (Table 1), was defined according to the Taguchi method. The LPA, filler and styrene contents (by weight of resin) were varied from 5–20%, 0–40% and 0–8%, respectively. The levels of gel times (1, 3 and 10 min) were chosen to investigate the effects of reaction rate. The injection pressure and temperature gradient were varied from 207–621 kPa and 5–15 °C, respectively.

2.2. Surface roughness measurement procedure

A Taylor Hobson Form Talysurf Series 2 stylus profilometer was used to measure the roughness profile of the plates. The location of

Table 1
Experimental test matrix

Exp. #	LPA (%)	Styrene (%)	Filler (%)	Gel time (min)	Temperature gradient (°C)	Injection pressure (kPa)
1	5	0	0	1	5	207
2	5	4	20	3	10	414
3	5	8	40	10	15	621
4	10	0	0	3	10	621
5	10	4	20	10	15	207
6	10	8	40	1	5	414
7	20	0	20	1	15	414
8	20	4	40	3	5	621
9	20	8	0	10	10	207
10	5	0	40	10	10	414
11	5	4	0	1	15	621
12	5	8	20	3	5	207
13	10	0	20	10	5	621
14	10	4	40	1	10	207
15	10	8	0	3	15	414
16	20	0	40	3	15	207
17	20	4	0	10	5	414
18	20	8	20	1	10	621