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Studies on the mouldability of structural foams in hybrid moulds

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A B S T R A C T

In the context of the research project Hybridmould 21, studies on the mouldability of structural foams using hybrid moulds have been carried out. Hybrid injection moulds are considered as an alternative for prototype series or short production runs of large parts. In hybrid moulds the moulding elements (blocks or other inserts) are manufactured in alternative metallic materials or synthetic materials typically using in rapid prototyping. Thermoplastic structural foams are moulded by injection moulding using injection pressures lower than in than in conventional injection moulding. The structural foam results from a dispersed gaseous phase, which derives from the expansion of a chemical blowing agent usually compounded in a masterbatch. In this project, thermoplastics and thermosets were used (PP, ABS and PUR) using a hybrid mould instrumented for temperature, pressure and expansion force. The moulding block was manufactured by vacuum casting of an epoxy composite. In this paper are mainly discussed the results obtained on liquid injection moulding polyurethane resins in the hybrid mould.

A R T I C L E I N F O

Keywords:
Hybrid moulds
Structural foams
Rapid prototyping techniques
Low pressure injection moulding
Reaction injection mould

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1. Introduction

The highly competitive modern market, the low life cycles of the products and the short time to market are the main challenges for the industries that need to reduce costs and manufacturing times [1, 2]. For some industries (e.g. automotive and electronic), the search for alternative routes for design and manufacture of tools for prototype or short production series of plastics parts lead to consider the resource offered by rapid prototyping and tooling (RPT) techniques and non-conventional manufacturing techniques [3]. Vacuum casting is a RPT process that allows manufacturing soft tools with accuracy and good surface finishing in epoxy composites [4]. The main advantage of this process is the short time to obtain freeform moulding blocks in comparison to conventional machining. In this way, it is possible to reduce the cost of comparable conventional tools by 40 % and the lead time to 2–5 weeks [5, 6]. Generally, epoxy resins filled with metallic powder (usually aluminium) are used to improve thermal and mechanical properties [7]. Thus, the vacuum casting is ideal for quick manufacturing of the moulding blocks used in the hybrid moulds [8].

The hybrid mould concept was developed to meet the market demands for shortest time-to-market and lower costs. These moulds combine a structure manufactured conventionally and moulding blocks produced by RPT (typically vacuum casting) and are a good solution for prototype series and short production series [1, 9]. They are made with materials with thermal and mechanical properties different from steel, leading to longer processing cycles and demanding lower injection pressures [10, 11]. Therefore, moulding processes involving low processing pressure, namely injection moulding of structural foams and reaction injection moulding (RIM) are ideal to be used with hybrid moulds.

Structural foams (SF) moulded by injection moulding develop a structure consisting of a low density cellular core, and a solid skin with density similar to thermoplastic. An inert gas is added at the molten thermoplastics to promote the cellular structure; chemical blowing agents (CBA) are the most common in SF injection moulding [12]. The polymer is blended with a CBA and then a short shot is injected in the mould under controlled temperature and pressure conditions. As soon as injection ends, the blowing agent expands and the foam fills completely the impression [13]. The typical thickness of a SF is between 4 and 9 mm, the density reduction is normally 10 % to 35 % and the pressure in the impression is approximately 4 MPa, an order of magnitude lower than in conventional injection moulding [14].

RIM involves the chemical reaction between two or more liquids, allowing that the mixture and polymerization occurs inside the mould [15]. The RIM process use reagents with low viscosity, which requires low pressure to fill large and complex parts. The quick filling of the impression can result in turbulent flow and formation of air bubbles. However, there are systems with fast reaction that can solidify before the complete filling, causing incomplete parts [16]. RIM is more appropriate to produce thick and large parts, with shorter cycle time. For small parts, this process is less competitive [17]. The low viscosity of the raw materials and the reduced pressure during processing results in lighter and cheaper moulds, which can be manufactured in alternative materials (e.g. filled epoxy resins). Consequently RIM is usually seen as an alternative for short run and prototype series that become economically viable. The main problems of RIM are the poor surface quality and voiding, and flash in the final parts, making it necessary finishing operations, to a cost in the final part [15].

2. Introduction

2.1 The test part

The shape and main dimensions of the test part in this work are shown in Fig. 1. This is a test part for morphological, structural and processing studies in SF moulding obtained either by injection molding and RIM. The development plastics part is 5 mm in thickness, which is typical in SF injection mouldings. The features in the part (castles, ribs and ledges) were designed to assess their processability in low pressure injection processes (SF injection moulding and RIM).

2.2 The tool

The tool used for moulding is a hybrid mould constituted by a steel structure and a moulding block assembled in the ejection side, which was manufactured by vacuum casting. The structure of the hybrid mould is sketched in Fig. 1 (right). This mould was instrumented with one Kistler type 9204B load cell (L), one Kistler type 6157B pressure sensor (P1), and three Priamus type N 4008B temperature sensors (T1, T2 and T3). The position of the temperature and pressure sensors on the mould surface is shown in Fig. 2.

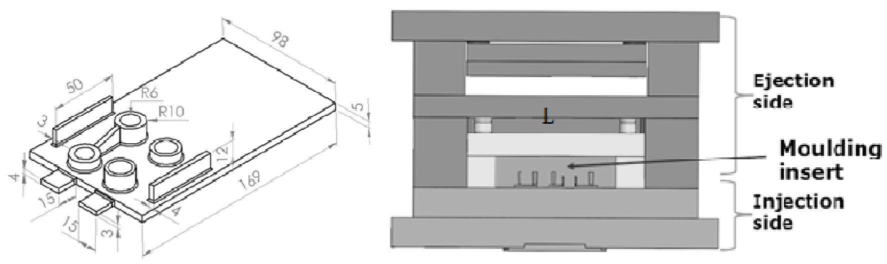

Fig. 1 Geometry and main dimensions of the plastics part (left), structure of the corresponding hybrid mould (right)

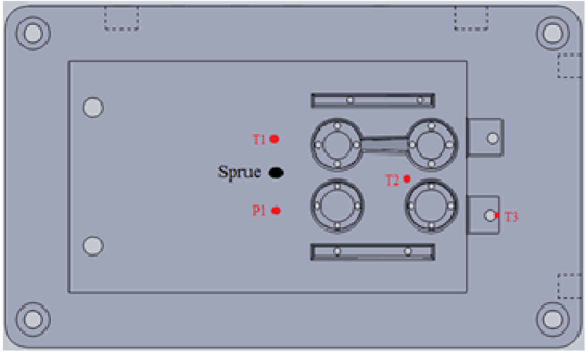

Fig. 2 Layout of the sensors in the hybrid mould

2.3 Materials

The moulding block was produced in an epoxy resin composite Biresin L74 (Germany) filled with 60 wt % of aluminium powder. The thermal and mechanical properties of this composite as mentioned by Martinho et al. [10] are shown in Table 1.

Table 1 Properties of the epoxy composite [10]

Properties	Biresin L74 + 60 % Al
Specific gravity	1.65 $Mg \cdot m^{-3}$
Specific heat	1279.19 $J \cdot kg^{-1} \cdot K^{-1}$
Thermal conductivity	0.606 $W \cdot m^{-1} \cdot K^{-1}$
Thermal diffusivity	0.286×10^{-6} $m^2 \cdot s^{-1}$
Coefficient of thermal expansion	6.00×10^{-5} K^{-1}
Flexural modulus (20 °C)	5.0–6.0 GPa

The SF mouldings were produced in two materials: polypropylene (PP) Domolen 1100N (Belgium), and acrylonitrile butadiene styrene (ABS) Kumho 710 (Korea). CBA masterbatches, Tracel PP 2200 SP and Tracel IMC 4200, were used for PP-SF and ABS-SF, respectively.

The RIM mouldings were produced with two polyurethane (PUR) systems: Biresin RG 53, from Sika (Germany) and Daltorim ED 12160, from Huntsman (USA). The Biresin RG 53 is a compact system with specific gravity of 1.20 $Mg \cdot m^{-3}$ with properties similar to PP and high density polyethylene (HDPE). The Daltorim ED 12160 is an integral foam system that allows obtaining low density mouldings (typically 0.40–0.50 $Mg \cdot m^{-3}$), especially adequate for thicker parts (4 mm to 20 mm), produced in non-metallic moulds. The main properties of these RIM systems are presented in the Table 2.

Table 2 Properties of RIM systems

Parameter	Biresin RG53	Daltorim ED 12160
Specific gravity (Mg/m3)	1.20	0.40–0.50
Pot life (s)	60	72
Demoulding time (min)	10	10
Curing time (day)	1	1

2.4 SF injection moulding

The mouldings were produced with a Victory Spex 50 machine (Engel, Austria). The machine was equipped with a shut-off nozzle to avoid the drooling of the melt. Two thermoregulators Piovan THN6P (Italy) were used to control the mould temperature. The monitoring signals from the sensors were acquired with a Multi Daq 8101A data acquisition system (Priamus, Switzerland).

The processing conditions were selected following similar studies by Esteves el al. [18] and are detailed in Table 3. To study the mouldability of the part four levels of mould filling were used in the injection of PP and three for ABS.

Table 3 Processing conditions of SF injection moulding [18]

Parameter		PP	ABS
Injection temperature (°C)		230	240
Mould temperature (°C)	Core	70	70
	Cavity	20	20
Cooling time (s)		200	170
Filling of mould (%)		80 58 90 95	85 90 95
Chemical blowing agent (wt %)		3 4	

The use of non-metallic materials in the moulding block (epoxy composite with lower thermal conductivity) determined the use of different temperatures in the core and the cavity sides of the mould.

The injection temperature was selected according to the material manufacturer recommendations and the decomposition temperature of the CBA masterbatch. The cooling time was determined experimentally (ejection when the moulding was sufficiently rigid for not warping).

2.5 Reaction injection moulding (RIM)

To produce the PUR mouldings the high-pressure foam-producing CMC HP40/2P (Cosmec, Italy) RIM equipment was used.

The processing conditions (Table 4) were selected according to the material manufacturer recommendations and experimental studies.

Table 4 Processing conditions of RIM process

Parameter	Daltorim ED 12160	Biresin RG 53
Mould temperature (°C)	30	20
Resin temperature (°C)	23	23
Mixing ratio (I/P)*	1.10	0.75
Flow rate (g/s)	100	
Mixture pressure (MPa)	ca. 18	

(*isocyanate/polyol)

3. Results

3.1 SF injection moulding

SF injection moulding is an unstable process for low levels of mould filling. For PP and at 80 % of mould filling, it was verified that the mouldings were not completely filled. For ABS, due to its higher viscosity, at the same level of 80 % of mould filling it was not possible to obtain complete mouldings. For higher levels of 85 % and 90 % the process became unstable and some mouldings are incomplete (Fig. 3).

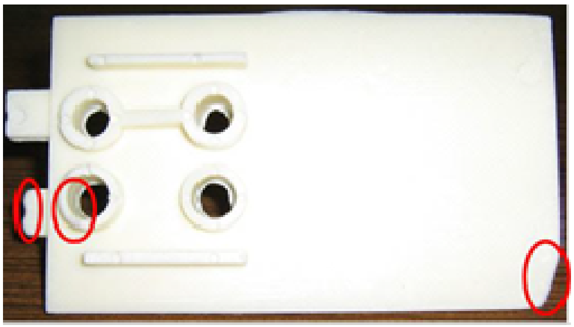

Fig. 3 ABS-SF incomplete moulding

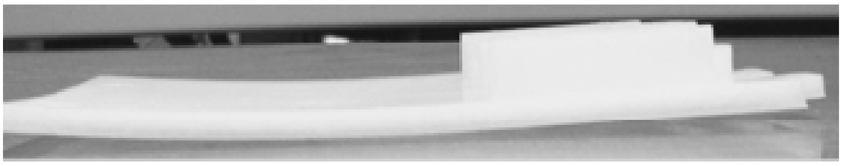

Fig. 4 Warpage in PP-SF moulding

The use of hybrid moulds, with different materials (composite epoxy and steel) in the core and the cavity, lead to varying shrinkage over the mouldings. The thermal conductivity of steel is about 40 W·m^{-1}·K^{-1}, whereas in the epoxy composite is much lower, 0.61 W·m^{-1}·K^{-1}. Thus, very different cooling rates are required in the two mould sides.

Semi-crystalline materials as PP are more prone to warpage, because in the slower cooling side of moulding (the epoxy composite side) more crystalline structures develop. In the steel side the cooling is faster and there is not time enough for full development of the crystalline structures. Thus, in the PP-SF mouldings, due to this inhomogeneous crystalline distribution, there is more warpage. The Fig. 4 shows a warped moulding.

The successive temperature and pressure cycles, and the ejection friction leads to the degradation in the moulding surface of the epoxy composite moulding block, as shown in Fig. 5. This degradation was more noticeable after 1000 injection cycles and in the more featured zone.

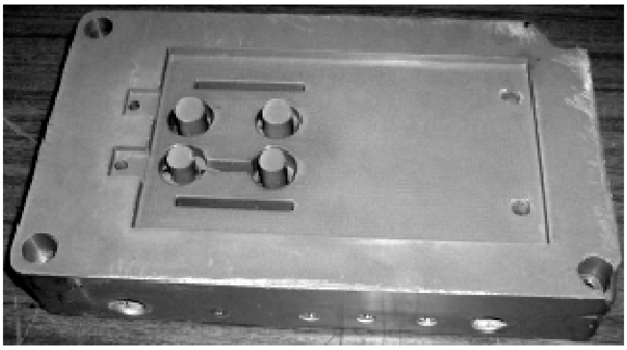

Fig. 5 Composite moulding block after 1000 moulding cycles

SF injection moulding monitoring

A typical plot of pressure and clamping force during the injection cycle is show in Fig. 6.

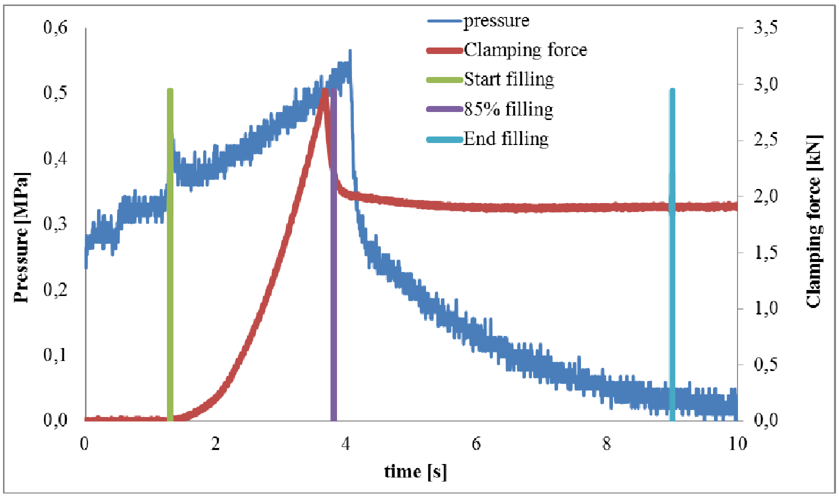

Fig. 6 Pressure and clamping force evolution in SF injection moulding

Table 5 Impression pressure data (MPa)

	3 wt % CBA				4 wt % CBA			
% fill	80	85	90	95	80	85	90	95
PP	0.52	0.54	0.56	0.58	0.50	0.52	0.54	0.57
ABS	-	0.73	0.79	0.80	-	0.65	0.73	0.73

Table 6 Clamping force data (kN)

	3 wt % CBA				4 wt % CBA			
% fill	80	85	90	95	80	85	90	95
PP	1.80	2.49	2.91	3.34	2.05	2.30	2.51	3.17
ABS	-	-	3.76	4.99	-	4.06	4.54	5.19

When the injection phase starts the pressure and clamping force increase linearly until the required level of mould filling is reached. The complete filling is promoted by the CBA expansion, with significantly lower pressure and clamping force.

Due to the force in the mould resulting from the injection, there is a peak at the end of the injection phase. It drops abruptly as soon as the injection pressure is released. The clamping force remains constant until the end of the moulding cycle, while the pressure decreases, being zero at the end of the mould filling.

In Table 5 and Table 6, the results of the SF injection moulding monitoring are presented. Upon increasing the level of mould filling, there is a rise in pressure and clamping force in the impression, as a result of the higher volume of material injected. Nevertheless, it is verified that the pressure and clamping force are an order of magnitude smaller than in conventional injection moulding.

3.2 Reaction injection moulding

In the RIM process the same hybrid mould was used, in spite of it having been designed for SF injection moulding. Consequently it is not the most suitable for RIM due to the inadequate sprue and venting system, and it was difficult to obtain mouldings without air bubbles. a part produced by RIM is shown in Fig. 7.

The use of moulding blocks manufactured in non-metallic materials can cause more adhesion between the moulding insert and the part [19]. Thus, a silicone release agent was used to improve the ejection of the moulding and increase the life time of the tool. In this study more than 100 parts were moulded without damaging of the moulding surface.

The aspect of the moulding surface after being used in SF injection moulding and RIM can be observed in Fig. 8.

RIM does not require cooling as in SF injection moulding, as the temperatures during the exothermic polymerisation reaction are relatively lower than in injection moulding. Therefore, the mouldings are less susceptible to warpage. On the other hand, as RIM involves the reaction of two liquids and produces a low crystalline and quasi-isotropic material, there is no warpage of the mouldings.

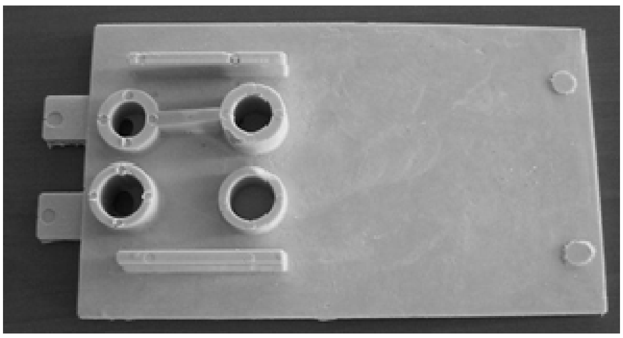

Fig. 7 PUR moulding produced by RIM

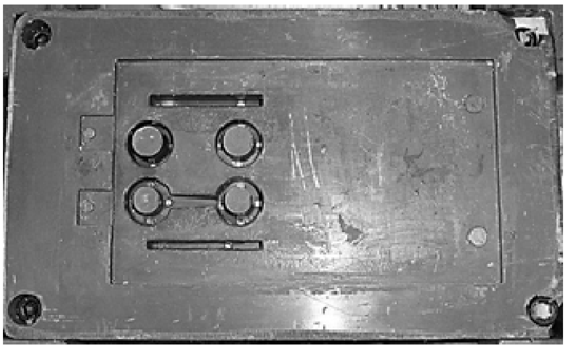

Fig. 8 Moulding surface after use in RIM processing

RIM monitoring

RIM is an exothermic process that causes a slight increase of temperature in the mould. The monitoring of the temperature and pressure was performed only in the Daltorim mouldings. A typical plot of the temperature evolution during the process is shown in Fig. 9.

The pressure in this system is negligible. Thus, lighter and less expensive moulds can be used.

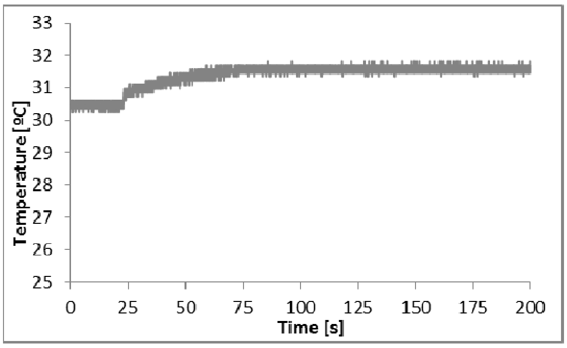

Fig. 9 Typical temperature during the RIM process

3.3 SF injection moulding vs. RIM

As a result of the physical properties of the corresponding raw materials and the level of filling there is a large variation in the weights of the mouldings in the various conditions, as shown in Table 7.

Compact RIM materials, as Biresin RG 53, are denser than usual thermoplastics. However, as integral foam systems (PUR Daltorim ED 12160) it is possible to reduce approximately the weight by one third. SF injection moulding may reduce the moulding weight by 20 %.

The RIM cycle time is ca. 600 s, which is longer than the SF injection moulding (ca. 120 s), but the moulds used in SF injection moulding can be more expensive than RIM process, which may balance the final product cost.

The RIM parts have some flash in the parting line and mould vents implying frequently the need of finishing operations.

Table 7 Results of the mouldings weight

Material	Filling (%)	Weight (g)
PP-SF	80	61.4
	85	65.3
	90	69.2
	95	73.1
ABS-SF	85	80.4
	90	84.8
	95	89.5
Daltorim ED 12160		58.3
Biresin RG 53		155.8

4. Conclusion

The hybrid moulds are a good solution to manufacture short series of the plastic parts. Thus the low pressure moulding processes (SF injection moulding and RIM) combined with hybrid moulds can be a solution to produce prototype parts and/or non-conventional parts (higher thickness) within a short lead time and with reduced cost.

SF injection moulding is a process somewhat unstable, requiring great control of processing conditions to achieve desired quality parts. The moulding pressure is lower than conventional injection moulding, the mould temperature and the rheological characteristics of melt (the melt should have low viscosity) are very important for the stability of the injection process and to produce good undamaged parts.

In RIM the pressure and temperatures are significantly lower than in SF injection moulding. Therefore, the tools in this process may last longer than in SF injection moulding. However, in this process it is essential a good mould design to allow the adequate filling of the mould cavity and an efficient venting system, which allows obtaining parts free of the bubbles.

In SF injection moulding the clamping force and impression pressure are an order of magnitude less than conventional injection moulding.

As a final conclusion hybrid moulds are a good solution for low pressure processes, as SF injection moulding and RIM.

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