PROCESS AND MOLD DEVELOPMENT OF DIRECT LONG FIBER REINFORCED FOAM INJECTION MOLDING ON THE EXAMPLE OF POLYCARBONATE AND GLASFIBERS

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Abstract

To achieve the demands of lightweight design in the automotive or aerospace industry it is necessary to optimize certain composite material groups with respect to their lightweight potential. Sandwich composites generally consist of a core which is coated with two face-layers. Task of the core is to transfer shear loads, while the face-layers absorb the tensile and compressive loads occurring at bending stress and are relevant for the surface quality.
Current research aims to increase the efficiency of said sandwiches while minimizing the weight per area by using for example (fiber-) reinforced face-layers. It is also attractive to reduce the number of manufacturing steps needed to produce a sandwich composite. This can be achieved by connecting the face and core layers in-situ by a so-called in mould assembly process.
As an approach to create these benefits, the thermoplastic foam injection molding (FIM) – a special injection molding process – is used in combination with a single material system.
Within this work, foamed and/or long fiber reinforced polycarbonate blanks were manufactured using a combined foam injection molding and compounding process. The different blanks - unreinforced polycarbonate (PC), fiber reinforced PC, foamed PC and fiber reinforced and foamed PC – were produced using a special developed and designed injection mold, which – amongst other features like inserts for functional elements – enables an insight into viscosity and shear rates of the injected material system. Several specimen were tested on their Charpy impact strength and their fracture surface was investigated using SEM images to verify the fiber-matrix bonding.

1. Introduction

Sandwich structures commonly consisting of face sheets (often reinforced with glass fiber material) and a foam core are lightweight design solutions used in structural applications prone to bending load or needing high energy absorption in crash events [1].
Thomason [4] investigated “the influence of fibre length and concentration on the properties of glass fibre reinforced polypropylene” via injection molded long and short fiber reinforced polypropylene (PP). The mechanical properties (modulus, strength, impact) of the used PP increased with the length of the glasfibers and Thomason established a “critical fiber length” where the properties of the

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composites reaches e.g. 90% of the maximum. This critical fiber length is different for each mechanical property and cannot be transferred directly to other material systems (like PC reinforced with glassfibers).
The benefits of long fiber reinforced sandwich structures in combination with the industrial scale foam injection molding process are investigated in scientific studies which also show the feasibility of a direct compounding/injection molding process [2,3]. After the fiber, gas and melt are comingled inside an extruder and transferred to the injection unit, the injected composite immediately hardens inside the mold wall to a solid fiber-reinforced wall and the core is able to foam. The high design freedom of injection molding allows a very complex and 3D part geometry with high lightweight potential [3].
Recent studies on foamed PC show the potential of this unfilled material and the correlation of process – structure – properties [5]. Bledzki et al. found, that PC either fails ductile or brittle depending on testing temperature, specimen thickness and notch geometry. It was investigated, that the Charpy impact strength increased up to five times comparing the compact to the micro-foamed specimen while failing brittle. When ductile fracture occured the specimen with micro-foam structure always display lower Charpy impact values.
To get an complete understanding of the influence of the manufacturing process to the structure and subsequently to the properties of foam injected reinforced material it is necessary to collect all process relevant data like e.g. pressure and temperature inside the mold, temperature of the melt and injection speed. Additional important parameters for the process characterization like viscosity and shear rate of reinforced or gas-laden melt can be obtained by methods suggested in [6] and [7] using a mold or an in-line rheometer. To obtain data for the viscosity measurement the rheometer used in [6] – a modified injection moulding nozzle – performed “air-shots” where the nozzle was moved back from the mold and the extrudate exited from the maschine. The study also shows in particular a reduction of fiber breakage through foaming wheras the viscosity trials were conducted with said nozzle and the trials on fiber length analysis without it. Therefore the fibers and the polymer used for viscosity messurement skiped the damages inside the mold – e.g. resulting from longer dwell times or sharp edges inside the hot runner – possibly leading to incorrect associated results.

Based on this findings and the aim to investigate fiber reinforced and foamed polycarbonate this paper shows the adaption of the direct long fiber reinforced foam injection molding process with a mold developed to investigate the viscosity of the reinforced/foamed material.

2. Experimental

2.1. Materials

The polymer used is Polycarbonate Makrolon 2605 supplied by Covestro. The material has a melt flow rate of 12 g/cm³ (ISO 1133, 300°C/1,2 kg). The reinforcement with glassfibers is realized with TufRov 4588 supplied by PPG. The fibers have a optimized sizing for long fiber reinforced processing and compartibility with polycarbonate. Nitrogen is used as physical blowing agent.

2.2. Process

The FIM process consists of an extruder and injection molding unit which are connected by a heated melt channel (Fig. 1). To combine the continuous extrusion process with the discontinuous injection molding process a melt buffer is installed.
The polymer (+ additives) as well as continuous glas fibers are directly fed into the extruder. The gas (nitrogen) is injected into the molten polymer close to the extruder die.
To combine the continous extrusion process with the discontinuous injection molding process a melt buffer is installed on top of the melt channel. While injecting polymer into the cavity, the buffer takes in the melt coming out of the extruder and buffers it for the next shot.

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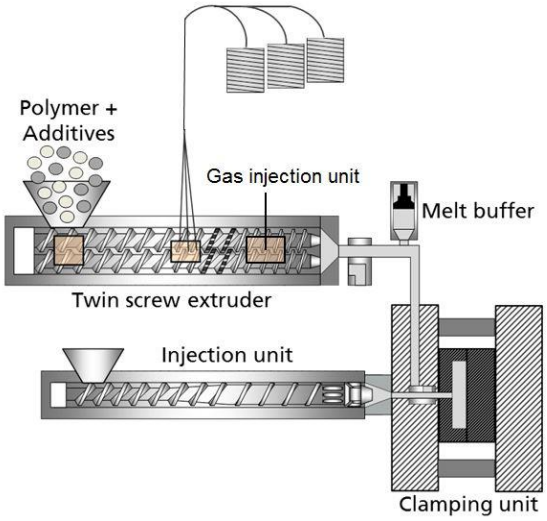

Figure 1. Principle of direct compounding of LFT in injection molding (D-LFT-FIM) [2]

The trials were conducted on the injection molding/compounding machine ENGEL duo 700 pico combi M compounder equipped with a twin screw extruder from Leistritz, model ZSE 40 MAXX, at the Fraunhofer Institute for Chemical Technology in Pfinztal (Fig. 2).
The clamping force of the injection unit is 7000 kN with a maximum injection volume of up to 4160 cm³, an injection speed of up to 945 cm³/s and an injection pressure of up to 2090 bar.
To feed the polymer into the extruder, a gravimetrical scale (FlexWall® of Brabender, with a Congrav® OP1 control) is used. For injecting the gas into the extruder a DSD 500 gas injectin unit of Maximator GmbH is used.

Figure 2. ENGEL duo 700 pico combi M compounder

To compare the influence of fiber-reinforced and/or foamed blanks to unreinforced blanks the polycarbonate is added into the extruder to always undergo the same thermal history.

2.3. Mold

A special equipped mold for investigations on long fiber reinforced foam injection molded parts was designed and is illustrated in figure 3. To operate the extruder in a reasonable process window and to simultaneously combine it within the restrictions of the scientific test specimen production (little shot volume compared to the projected surface area) a secondary cavity is necessary to get rid of the excess material without filling the melt buffer entirely leading to an abort of the process. As general specifications the tool has a main cavity for the production of blanks (250 mm x 500 mm) with adjustable wall thicknesses (1 – 4 mm). The main cavity is equipped with three individually selectable and hydraulic operated needle shut-offs (∅ = 8 mm) for part gating and optimized to reduce fiber breakage.

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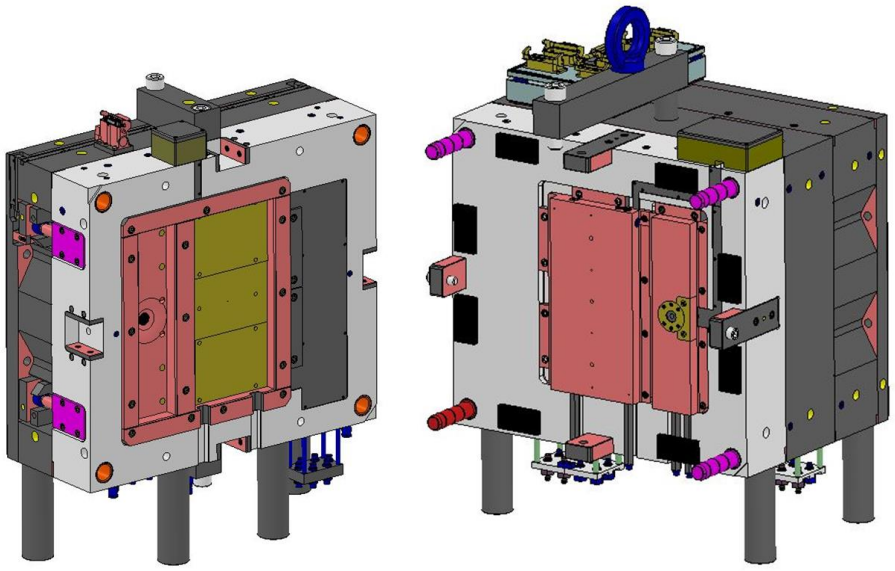

Figure 3. Injection Molding tool (CAD image)

With three additional and changeable mold inserts for functional elements (abruped changes in wall thickness, bosses, ribs and grained surfaces) illustrated in figure 4, it is possible to investigate flowing behavior of the melt and filling of the cavity. To vary the surface-layer to core ratio in a wide range and to obtain high surface qualities while foaming the mold can be used in a variothermal process where the inserts are heated and cooled alternating.
Four combined pressure and temperature sensors as well as two pressure sensors integrated in the main cavity surface enable full sensory insight during the injection moulding process .

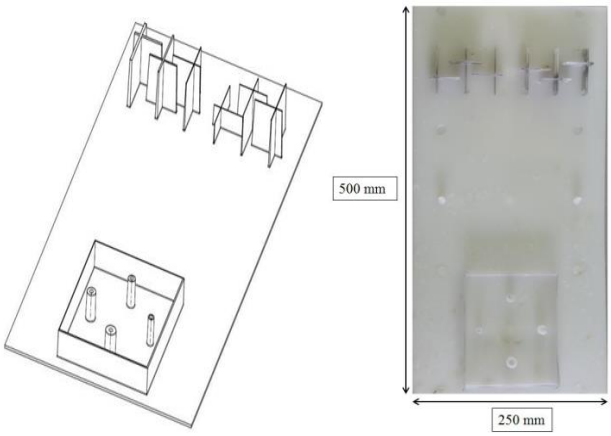

Figure 4. Functional elements; drawing (left) and made of HDPE (right)

Additional on dealing with the excess material, the secondary cavity is holding a fourth shut off valve and a device to mesasure the pressure and temperature before and after a capillary die (Fig. 5).
This device was developed according to Zhang et.al. [6], who modified the nozzle of an injection molding maschine to create an in-line rheometer. The benefits of a rheometer inside the mold is, that the reinforced and/or gas-laden polymer has the identical processing history as the final part and the identical injection parameters are used. With the obtained results for pressure and temperature the viscosity and shear rate can be determined according to [6] and [8], which allows a unique in-situ insight on the viscosity of foamed and/or reinforced polymers during processing. There are three changeable capillary dies with different L/D ratios to correct for entrance effects by using the Bagley correction method [8].

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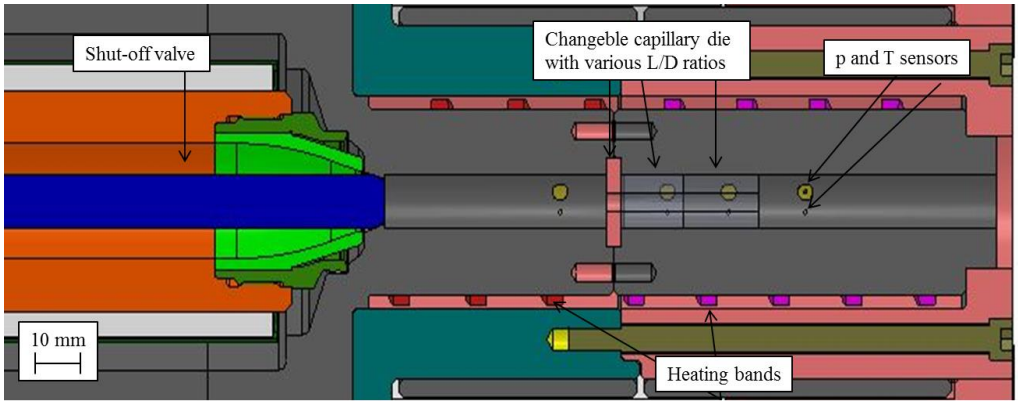

Figure 5. Crossection of the capillary rheometer

The apparent shear rate $\dot{\gamma}_{ap}$ is describes as:

$$\dot{\gamma}_{ap} = 32Q/\pi D^3 \text{ [8]} \quad (1)$$

where D is the diameter of the capillary die bore (in mm) and Q is the volume flow rat (in mm³/s).
For a capillary die the apperent shear is described as:

$$\tau = pD/4L \text{ [8]} \quad (2)$$

where p is the test pressure and L the length of the die.
With the results of equation (1) and (2) the apparent viscosity η_{ap} can be calculated as ratio $\dot{\gamma}/\tau$ and ultimately the true shear rate/shear stress/viscosity can be calculated by using several correction methods (Bagley and Weissenberg-Rabinowitsch)[8].

3. Results

With the described system of extruder, injection molding machine, gas injection unit and mold several sheet-like blanks were manufactured. Figure 6 illlustrates the mold filling study of the polycarbonate with the following parameters:

- Melt temperature: 300 °C
- Mold temperature: 100 °C
- Injection volume flow: 100 cm³/s
- Injecting through the lower shut-off valve.

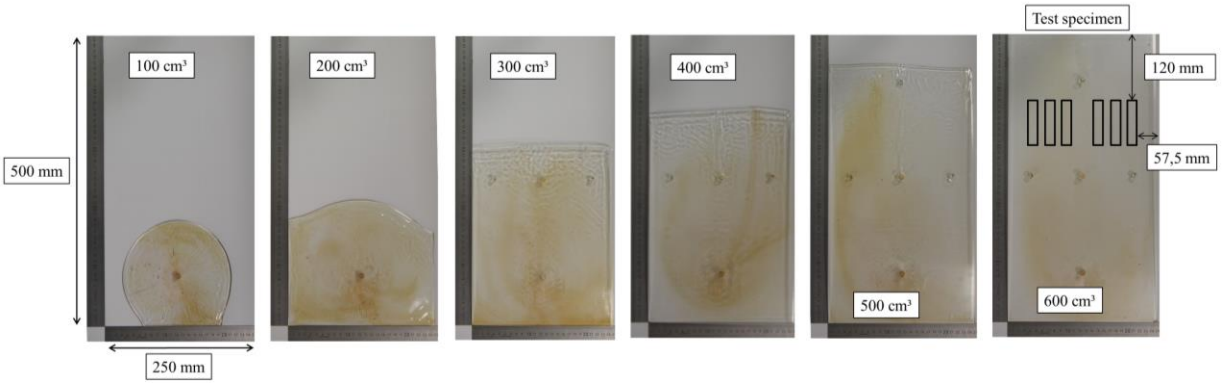

Figure 6. Mold filling study and position of the retrieved Charpy specimens

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The mold filling study (injection into a 4 mm cavity with the lower shut-off valve) illustrates the melt front spreading circular around the gate. A linear melt front is formed about half way through the cavity as seen in figure 6 at 300 cm³. The test specimen have to be retrieved from an area with uniform melt flow to avoid inhomogenities of the material/fibers [9]. The slight discolorations of the blanks are due to the fact that inside material remainings can not be removed completely out of compounder/injection unit and hot runner system. Within the trials this effect is enhanced by fiber reinforcement and cannot be avoided with conventional and reasonable countermeasures. Figure 7 illustrates the cross-section of the manufactured blanks and shows the sandwich structure of specimen B and D due to the foaming process. Within this trials the goal of the foaming step was to achieve a maiximum of weight reduction with simultaneous filling the mold entirely.

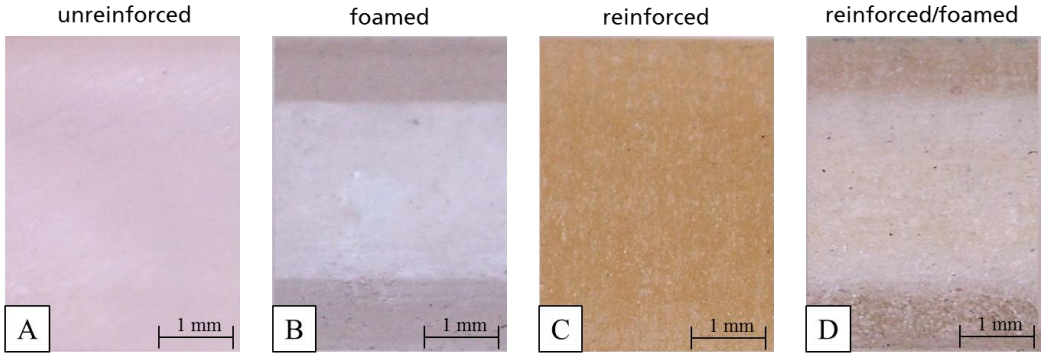

Figure 7. Cross-section of the specimens (unreinforced – A, foamed – B, reinforced – C, reinforced and foamed – D)

The manufactured specimens were weighed and tested on Charpy impact strength (Table 1.), which was conducted according ISO 179-1:2010 [10] with flatwise orientation and performed on an impact pedulum HIT5.5P from Zwick/Roell. The parameters set while manufacturing the blanks respective specimen were unreinforced (0 wt-% fiber content and 0 wt-% gas content - specimen A), foamed (0 wt-% fiber content and 0.3 wt-% gas conten - specimen B), reinforced (20 wt-% fiber content and 0 wt-% gas conten - specimen C) and reinforced combined with foamed (20 wt-% fiber content and 0.3 wt-% gas conten - specimen D).

Table 1. Parameters and properties of the tested specimens

Specimen Type	*Fiber content (wt-%)*	*Gas content (wt-%)*	*Specimen Weight (g)*	*Charpy impact strength (kJ/m²)*
A	0	0	4.08 ± 0.08	n.v.[1]
B	0	0.3	3.23 ± 0.05	n.v.
C	20	0	4.71 ± 0.08	55.7 ± 2.75
D	20	0.3	3.68 ± 0.15	43.2 ± 1.6

After breaking the specimens, a SEM analysis of the fracture surface (specimen C and D) was conducted on a scanning electron microscope SUPRA 55 VP from Zeiss at Fraunhofer ICT in Pfinztal (Fig. 8).

[1] n.v.: No values available due to the testing method.

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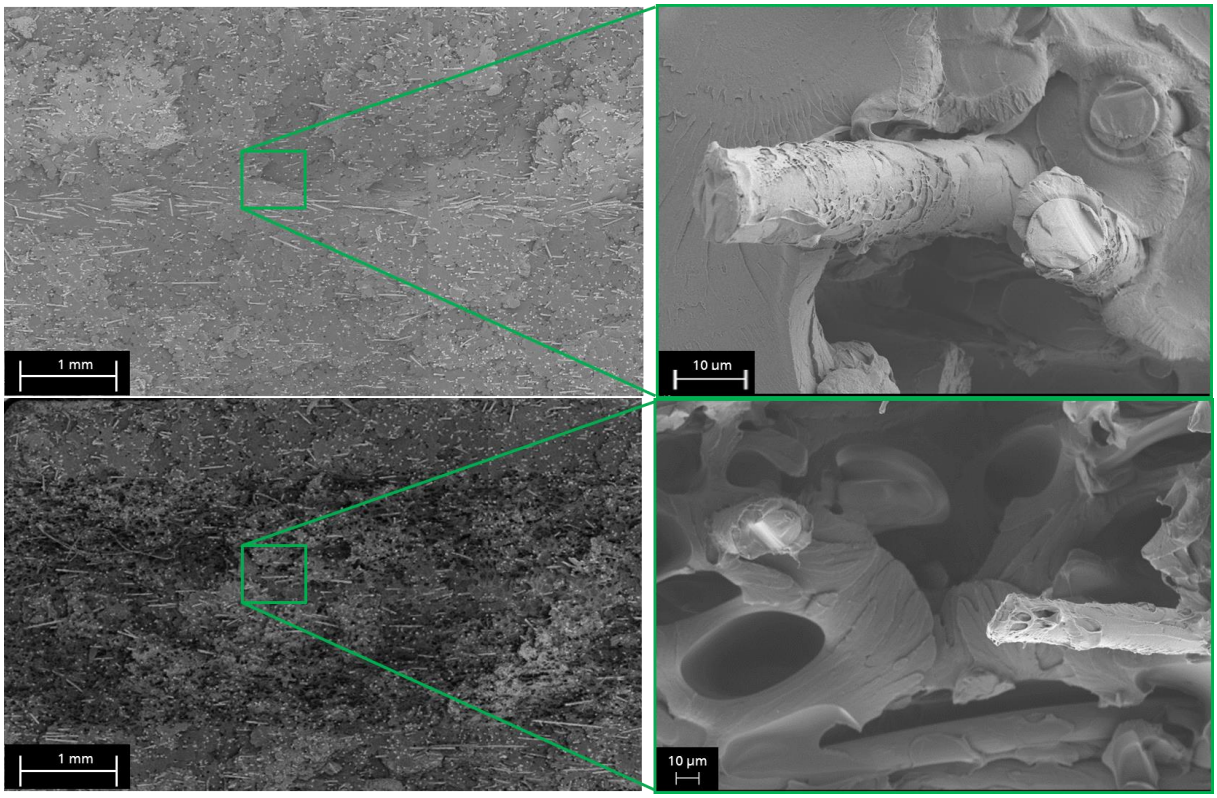

Figure 8. SEM images of specimen C (top) and D (bottom)

4. Discussion

All samples are manufactured with the same thermal history with the D-LFT-FIM process and compared to their weight and impact strength (Table 1.).
The weight reduction of specimen D (foamed and fiber reinforced) compared to specimen C (fiber reinforced) is in average 22 %. The charpy impact strength also decreases roundabout 22 %. This concludes no embrittlement through foaming or relative increase of Charpy impact strength of the specimen with the used process parameters. In contrast [5] states that – while using different types of foamed PC, notched test specimen and edgewise test directions – the Charpy impact strength increased up to five times the value of the compact specimen. The differences on geometry of the specimen, testing method and the fiber reinforcement could explain this material behavior. However the findings made in this paper have to be utilized carefully, because the approach of minimizing the weight while foaming can lead to inhomogeneous foam structure and distribution.
Specimen B and D exhibit a finely dispersed foam structure with a precise defined transition from face layers to center core (Fig. 7) with a greater surface-layer to core ratio at the unreinforced foam.
As illustrated with SEM images in figure 8 the fiber-matrix bonding is excellent as the fibers are covered in matrix after the impact test. When foamed, the reinforcing fibers are surrounded by matrix material and the foam builds a hollow strucuture around them. This increases the durability of the sandwich by reinforcing the supporting structure of the sandwich core.

5. Conclusions

Within this work, the D-LFT-FIM process has successfully been adapted to glass-fiber reinforced polycarbonat. Therefore an innovative, research injection molding mold was developed and put into

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operation. The mold contains functional elements and an unique capillary rheometer to collect information about viscosity and shear rates oft gas-land reinforced polymer melts.
Several different polycarbonate blanks, including reinforced and foamed ones, were manufactured in the direct injection molding/compounding process.
Specimen taken out of an area of uniform material structure have been tested and compared on their weight and Charpy impact strength. With the used injection molding, reinforcement and foaming parameters no embrittlement or increase of Charpy impact strength can be observed. The fiber matrix bonding and foam structure was validated by optical analysis using SEM images and was assessed good.

Further investigations on the structural and mechanical properties and their connection of the shown material system will be performed varying the process parameters.

Acknowledgments

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