PROCESS, MATERIAL AND PART CHARACTERIZATION OF THE INNOVATIVE DIRECT SMC PROCESS

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Abstract

For manufacturing of compression moulded parts with long fibre reinforcement and thermoset matrix the Direct Sheet Moulding Compound Process (D-SMC) has been developed. In this process the compound is being inline manufactured and subsequently directly moulded. In that way a consistent compounding process with constant material treatment is achieved, with very short processing times of minimum 15 minutes from mixing to molding.

A prototype manufacturing D-SMC line has been set up in full industrial scale in conjunction with a 3600 tons press. The process control is fully integrated from raw material dosing over compound manufacturing until compression moulding of parts. In this paper the characteristics of this new and innovative process have been investigated with respect to the achievable material and part properties.

Introduction

Over the last years the Direct SMC process has been developed in order to establish an integrated fully automated processing method for thermoset fiber reinforced compression moulded parts from raw material supply to the ready moulded parts. Multiple ways of continuous processing have been explored by several consortia and have been characterised, respectively. For obtaining material and part properties equal to SMC parts the way of incorporating the fibers needed to be optimized. The state of the art technology is nowadays the combination of a badge-to-continuous dosing unit for the liquid raw materials, compounding the resin filler paste in a twin screw extruder, compounding the fibers in on a sheet machine with subsequent fast maturation and direct compression moulding of the parts. In the following the process set up is described (cf Figure 1).

First resin, additives and filler are gravimetrically dosed into a twin screw extruder where the resin filler paste is being compounded as shown in the schematic process drawing in. As a twin screw extruder is being used for this compounding step a higher mixing quality in terms of dispersion, homogeneity and air entrapments can be realized compared to dissolver equipment. The resulting resin filler paste contains all necessary raw materials like resin, LPA, processing and wetting additives, peroxide and additives for controlling the paste viscosity. This mixture is being split into two equal streams and transferred into doctor boxes of the direct compounding machine. There the continuous glass fibre rovings are fed in, cut and compounded in between the resin filler paste sheets. After a fast maturation under elevated temperature the carrier film is being peeled off, the sheet is cut into the charge pattern and subsequently being stacked. The whole stack of charge pattern is than directly placed in the mould and the part is manufactured by compression moulding. Depending on sheet width, through put and material formulation the time from raw material to the ready moulded part is minimum 15 minutes.
A new pilot line is in operation for approx. one year at the Fraunhofer ICT in Germany. Many trials with different formulations and tests with different complex parts to characterize the material properties and quality consistency have been performed.

**Experimental Work**

In order to characterise this manufacturing method a Design of Experiment study has been carried out. The major target was to identify the effect material and process parameters on the material properties. Furthermore these parameters should be qualified within the investigated boundaries.

A Class A material formulation was chosen which represents the state of the art in conventional SMC technology. The glass fiber content was 28%wt and the CaCO₃ filler content was 180phr. The formulation also contained internal mould release agent, wetting agent and peroxide. All material parameters were kept at a constant level throughout this investigation except the thickening agent. The content of magnesium oxide has been varied.

The used Direct SMC line is a prototype line manufactured by Dieffenbacher and is in operation at the press center at the Fraunhofer ICT, Pfinztal, Germany. The Direct SMC line is in full industrial scale and has an output rate from 1 kg/min up to 8 kg/min. The sheet width is flexible and can be adjusted between 400mm and 800mm. In this trial campaign the sheet width was constant at 800mm and the throughput was constant at a rate of 1kg/min. The moulded part geometry was a Volkswagen Golf hood with Class A finish. The compression moulding pressure was at 100 bars and was reduced to 30% after 30 seconds. The whole curing time was 150 seconds.

For investigating the link between process parameters, thickening behaviour and resulting mechanical properties a Design of Experiment study has been executed utilizing the software MODDE 8.0. A screening model was chosen in an interactive D-optimal design. The parameters of the investigated parameter magnesium oxide content, temperature in the fast maturation zone and penetration depth of the rolls in the impregnation zone are given in
Table 1.
Table 1 Investigated parameters in the Design of Experiment study

<table>
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<tr>
<th>Exp No</th>
<th>Exp Name</th>
<th>MgO Content [phr]</th>
<th>Maturation Temperature [°C]</th>
<th>Impreg. Penetration Depth [mm]</th>
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The investigated responses to the parameters are flexural stiffness, flexural strength and Charpy impact strength. The flexural testing was executed according to the standard DIN EN ISO 178 and the Charpy impact test was executed according to the standard DIN EN ISO 179. The specimens were taken out from the charge pattern area of the molded hood and from the edge of the molded hood representing the flow area of the part. All specimens have been taken out in the same orientation transversal to the flow direction. In the following it will be distinguished between results from the charge pattern area and the flow area.

Results and Discussion

Based on the achieved results of the mechanical testing the best model was created describing the interaction between the investigated parameters and the mechanical characteristics within the borders of this investigation. The values for $R^2$, representing the fit of the model to the measured data, and $Q^2$, describing how good the model would deal with new, unmeasured data, are given in Figure 2. The $R^2$ value should be close to 1 and $Q^2$ should be higher than 0.5 for further use of the model. As this is the case except for the fit value ($R^2$) for flexural stiffness in the charge pattern area, the model is being used for the further investigation.

![Figure 2 Characteristic values for $R^2$ and $Q^2$ of the DoE model for the charge pattern area (left) and the flow area (right) for the investigated response of the mechanical properties](image-url)
In Figure 3 the results for the flexural stiffness from the charge pattern area and from the flow area are shown. In both cases the flexural stiffness is shown depending on the investigated factors maturation temperature, MgO content and penetration depth of the impregnation rolls unit.

Figure 3 Flexural stiffness in the flow area depending on a) maturation temperature and MgO content and depending on b) impregnation penetration depth and MgO content; Flexural stiffness in the charge pattern area in dependency on c) maturation temperature and MgO content and depending on d) impregnation penetration depth and MgO content
In the flow area it can be observed that with an increase of the maturation temperature the stiffness increases in a linear way, respectively. The MgO content doesn’t affect the flexural stiffness in the same way. In the flow area the flexural stiffness remains on the same level within the investigated variation of the MgO content (cf. Figure 3 a) and b)). That suggests that the temperature increase has a higher effect on the thickening compared to the MgO content. For the charge pattern area we can observe a contrary effect of the maturation temperature (cf. Figure 3 c)). With an increase of the maturation we can observe a decrease of the flexural stiffness. That can be explained by the higher viscosity, which leads to an improved fiber and filler transport in the compression molding step. The transported fibers and fillers lead to a local decrease of the stiffness in the charge pattern area and a local increase in the flow area, respectively. The MgO content has a low effect on the stiffness in the charge pattern area (cf. Figure 3 c) and d)).

The increase of penetration depth of the impregnation rolls leads to a decrease of the flexural stiffness in the flow area and in the charge pattern area (cf. Figure 3 b) and d)). This effect is higher at higher thickening levels. In the flow area the model suggest a strong decrease of the flexural stiffness with an increase of the penetration depth up to a local minimum. From this minimum the flexural stiffness increases with an increase of the penetration depth of the impregnation roll up to a certain level which is lower than at low penetration depths of the impregnation rolls. This local minimum cannot be observed in the charge pattern area, where the flexural stiffness decreases with decreasing penetration depth. Generally it can be stated that too high penetration depth applies too high pressure on the SMC sheets in the manufacturing process which leads to a squeeze out of the resin filler paste. That would explain the lower filler concentration and the lower flexural stiffness at deeper penetration depth of the impregnation unit.

The results for the flexural strength are shown in Figure 4 a)-d) in dependency of maturation temperature, MgO content and penetration depth of the impregnation unit. Generally a similar behavior of the flexural strength can be observed compared with the flexural strength. The flexural strength increases linearly in the flow area with an increase of the maturation temperature (cf. Figure 4a)). If the amount of MgO as thickening agent is increased, the flexural strength in the flow area is nearly constant with a slight increase at higher MgO values. In the charge pattern area the effects of higher maturation temperature and higher MgO contents is contrary, as the flexural strength decreases (cf Figure 4c)). This behavior can be explained by an enhanced fiber and filler transport in the compression molding step at higher viscosities. The viscosity is increased through higher maturation temperature and through higher MgO content, whereas the maturation temperature seems to have a stronger effect than the thickening agent content. The improved fiber transport leads to a local increase of the fiber content in the flow area and to a local decrease of the fiber content in the charge pattern area, respectively. As the glass fibers are the reinforcement in the material, higher mechanical loads can be borne in the flow area and lower loads can be borne in the charge pattern area, respectively.

In the flow area we can observe a quadratic curve of the flexural strength in dependency of the penetration depth of the impregnation unit (cf. Figure 4 b)). In the range of 30mm to 40mm of penetration depth the flexural strength decrease and reaches a local minimum. At higher values for the penetration depth from 40mm to 50mm we can observe an increase of the flexural strength. The flexural strength at higher penetration depth has a higher value compared to the values at the initial low penetration depth. In the charge pattern area we can observe a contrary behavior (cf. Figure 4 d)), as the flexural strength decreases at higher penetration depths of the impregnation unit. This effect is amplified at higher thickening agent loading. A possible explanation is that the deeper penetration depth of the impregnation unit applies higher pressure
to the sheets in the manufacturing process. That leads to a squeeze out of the resin filler paste and to higher overall fiber content. At higher viscosities these fibers are then transported into the flow area, where we can observe the improvement of the flexural strength.

Figure 4 Flexural strength in the flow area depending on a) maturation temperature and MgO content and depending on b) impregnation penetration depth and MgO content; Flexural strength in the charge pattern area in dependency on c) maturation temperature and MgO content and depending on d) impregnation penetration depth and MgO content
The Charpy impact strength in dependency on the maturation temperature, MgO content and the penetration depth of the impregnation unit is given in Figure 5 a)-d). The overall behavior is contrary to the discussed properties flexural stiffness and flexural strength.

Figure 5 Charpy impact strength in the flow area depending on a) maturation temperature and MgO content and depending on b) impregnation penetration depth and MgO content; Charpy impact strength in the charge pattern area in dependency on c) maturation temperature and MgO content and depending on d) impregnation penetration depth and MgO content

All four graphs show that the Charpy impact strength is increasing with an increase of the
thickening agent MgO. That can be explained through the wet through of the fiber bundles. If the wet through of the fiber bundles is too high and the wet out of the fibers is too good, the energy uptake in case of impact loads is decreasing. Once the viscosity is increasing the impregnation behavior of the resin filler paste is decreasing. This leads than to a worse wet out at higher MgO contents.

The maturation temperature is affecting the Charpy impact strength contrarily. With an increase of the maturation temperature we can observe a decrease of the Charpy impact strength (cf. Figure 5 a) and d)). The MgO is added upstream in the manufacturing process compared to the timing when the maturation temperature is applied. At that time in the process the material is already quite highly viscous and the elevated maturation temperature lowers this viscosity. With the reduced viscosity the wet through of the fiber bundles is enhanced leading to a reduction of the Charpy impact values.

In Figure 5 b) and d) it can be observed that the Charpy impact strength is increasing with higher penetration depth of the impregnation unit. In the flow area this behavior can be explained by the higher applied pressure in the impregnation unit at higher penetration depth levels. This improves the wet through of the fiber bundles and reduces the impact strength, respectively. In the charge pattern area a quadratic behavior can be observed, where the Charpy impact strength first increases with deeper penetration to a local maximum. After this local maxim the Charpy impact strength decrease to the same level as initially. This behavior needs more investigation of either the generated DoE model or the material itself.

**Conclusion**

In this presentation the material properties of the D-SMC process have been linked with the parameters maturation temperature, MgO content as thickening agent and penetration depth of the impregnation unit. It was found out that the material properties can be adjusted in the process by varying these parameters. For the mechanical properties flexural stiffness and flexural strength the compound viscosity seem to be the dominating factor, which is determined more by maturation temperature than by thickening agent content. The variation of the Charpy impact strength is more dominated by the content of thickening agent than by the maturation temperature. So depending on the requirements of the application the investigated material characteristics can be adjusted in the Direct SMC process. The penetration depth of the impregnation unit has a strong effect on the investigated material characteristics. In general for the investigated model it can be stated that with deeper penetration depth the mechanical properties decrease. At some properties the shape of the graph seems to be quadratic but this needs to be investigated further.

The Direct SMC process offers a unique chance where material properties of one formulation can be changed by adjusting parameters in the process online. This adds new degrees of freedom to the material class of compression molded long fiber reinforced thermoset composites. Future needs of applications in terms of higher diversity can be served through this.

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