Process-integrated material compounding for the sustainable manufacture of high-strength components

Fiber direct compounding for economical and resource-saving production

Dipl.-Ing. Martin Hoyer, ARBURG GmbH + Co KG, Loßburg

Abstract
The fiber reinforcement of plastics has long been an elementary process in automotive engineering for the targeted modification of component properties. As a result, the range of uses of plastics has been substantially expanded in recent years and further developments have been pushed forward continuously. The main areas of development include cost savings through the substitution of metallic materials, but also typical engineering plastics such as PA with PP, the improvement of sustainability factors such as recyclability, CO₂ footprint and energy consumption as well as increasing the economic efficiency of the production processes. The process presented here for the direct compounding of thermoplastic fiber-composite plastics on an injection-molding machine covers all of the development areas just mentioned.

1. Possible uses of long glass fibers and processing methods
Adapting materials as precisely as possible to component requirements is a basic prerequisite for an ideal component design and a high productivity. Particularly in the case of reinforced plastics, which are often used in technical applications or in automotive engineering, there thus is a desire not only for a flexible adjustment of material and processing parameters but also at the same time for stable and fully traceable processes. The use of fiber-reinforced materials in automotive engineering, whether with short or long glass-fiber reinforcement, has long been 'state of the art'. Above all, the use of materials with the longest possible fibers in order to improve the material properties offers potential in lightweight applications and in the improvement of sustainability indicators. The basic mechanisms and factors influencing the material properties are shown in Fig. 1.
In addition to reducing weight, fiber reinforcement can also be used specifically to improve component quality and mechanical properties with regard to strength and toughness (see Diagram 1).

Furthermore, the component can be given a different design during the design phase, thus laying the foundation for future developments of automotive components. Specifically, long glass fiber reinforced polypropylene (PP LGF) has, for example, material properties similar to aluminum together with a significantly reduced weight, which leads to material substitution and thus to lighter components. This also means that the long glass fiber reinforced polyamide (PA) previously used for metal substitution can in turn be replaced by long glass fiber reinforced polypropylene. Another advantage of polypropylene is its significantly lower water absorption compared to polyamide and its lower specific weight. When replacing polyamide...
with polypropylene, the focus is however less on weight reduction and more on the economic efficiency of the production processes. These economic considerations usually go beyond the injection-molding or compounding process per se and also include areas such as material selection, quality control and documentation. For this reason, processes that are of particular interest are those that can be easily integrated into the existing manufacturing process.

Diagram 1: Quantitative change in mechanical properties stiffness (black), strength (red) and toughness (blue) as a function of fiber length

There are various methods of obtaining longer fibers in components. Either prefabricated long glass fiber granulates are processed or raw glass fibers, usually off a spool of continuous glass fibers, are fed directly into the plastic melt by direct compounding (see Fig. 2).
In the pultrusion of long glass fiber granulate, continuous glass fibers are embedded or coated in a matrix material. If a thermoplastic matrix material is used, it must be melted before the glass fibers are embedded. Compared to direct compounding, additional energy is therefore required for the melting and the material is subjected to an additional thermal load with possible molecular chain degradation.

The advantages of long glass fiber granulate are their easy handling, as is generally the case when using plastic granulates, and in terms of material quality that the granulates are manufactured on an industrial scale under constant conditions. However, the wide range of long glass fiber granulates makes it necessary for the component design and the entire injection-molding process to be specifically tailored to the respective long glass fiber granulate. In addition, the long glass fiber granulate in question must also be stored in appropriate quantities. With direct compounding, on the other hand, only the basic materials, i.e. the matrix material and raw glass fibers, need to be procured and stored. The process allows great degrees of freedom with regard to fiber quantity and fiber length, since all important parameters can be set directly at the control unit of the injection-molding machine and can thus be individually adapted to the component in question.

It is possible to use a melt compounder in combination with an injection-molding machine for the in-line production of long glass fiber compounds. This type of compounding is an established process and is often used for the production of standardized parts in mass production.
The fiber direct compounding (FDC) process presented here is, on the other hand, a flexible and efficient process that feeds raw glass fibers directly into the plasticizing unit of the injection-molding machine. This makes the process particularly economical and, in addition, there is no need to use an additional compounder. The FDC process is therefore predestined for the production of challenging components in a wide range of variants.

The functional principle of fiber direct compounding (FDC)

In direct fiber compounding, long glass fibers are fed directly to the melt in the plasticizing cylinder of the injection-molding machine during the dosing process (see Fig. 3).

One or more strands are drawn off a spool of continuous fiber and fed to a fiber trimming unit. The continuous glass fibers are cut to the desired fiber length in the fiber trimming unit and fed into the plasticizing cylinder of the injection-molding machine via a twin-screw conveyor. The fibers are then worked into the plastic melt by the rotational movement of the plasticizing screw and homogenized. A special plasticizing screw with an adapted geometry is used for direct fiber compounding. This is significantly longer than a standard screw and has a relief area in which the fibers are fed to the screw.
The fiber trimming unit is equipped with suitable sensors and control technology to ensure the exact fiber length and quantity. The fiber trimming unit is integrated in the control system of the injection-molding machine and is functionally thus fully integrated into the plasticizing process of the machine (Fig. 4).

With the FDC process from ARBURG fibers with a length between 6 and 217 mm can be processed. Injection units adapted for this process are available for shot weights of 150 - 950 grams (PP GF 30).

2. Material quality and characteristics

The fiber length and its connection with the matrix plastic is of decisive importance to the quality and the physical properties of the component. In order to assess the quality of a material produced in the FDC process, it is compared with a material consisting of long glass fiber granulate.
In the FDC process it is therefore important for the fulfillment of quality and stability requirements to ensure a melt quality over different process conditions that is comparable to the pultrusion of long glass fiber granulates.

This is achieved by optimizing the molding process and by adapting fiber-direct compounding to the particular process conditions. Predefined sequences are available for controlling the injection-molding machine, and it is also possible to set different parameters individually, such as the fiber content in the component. This is effected, for example, by a process-dependent adjustment of the fiber feed during the dosing process. Compared to long glass fiber granulates, fiber direct compounding calls for a more detailed practical knowledge of the process and the relevant parameters. However, the time required for adjusting all of the parameters is manageable and can be divided into the sampling or setting-up processes that are necessary anyway.

Diagram 2: Comparison of the fiber lengths in the component in FDC and LGF (source: SKZ - excerpt from laboratory report on material testing)
The decisive factor for the quality and strength of the components is the mean fiber length and the fiber length distribution. In order to determine fiber lengths, the plastic portion of the components is removed thermolytically (ashing) and the remaining fibers are counted and measured in part by hand (see Fig. 5).

![Housing (right) and fiber content after ashing (middle)](source: ARBURG GmbH + Co KG)

Such investigations show that the FDC process, despite plasticization and injection into the mold cavity, has a greater proportion of longer fibers in the component than is the case with long glass fiber granulates (Diagram 2).

An advantage with regard to the fiber length is that in the FDC process the trimmed fibers are fed into the already plasticized matrix material, thereby reducing the strain on the fibers. The loss of long fibers due to fiber breakage during conveyance through the plasticizing screw and injection into the mold cavity is relatively low. This loss can be further reduced by designing the entire melt path for the lowest possible shear and fiber stress.

**Plant technology and quality assurance**

In order to meet the high quality demands made of components manufactured by the FDC process, all sub-processes that are directly involved in the injection-molding process are monitored by the control unit of the injection-molding machines in every production cycle. This includes, in particular, monitoring the FDC parameters, such as the fiber quantity or the suction forces. Thanks to a modern machine control system, the FDC process is easy to monitor and control and can be individually adapted to individual requirements and production conditions. In addition, the process data of each individual manufacturing process are recorded and saved in relation to the particular component. This also includes the data from VDI-Berichte Nr. 2369, 2020.
weighing the components immediately after removal from the mold. This means that weight deviations can be detected immediately after injection molding, documented and subsequently sorted into good and bad parts.

Fig. 6: Production cell with FDC unit as well as automated handling and weighing of the fiber-reinforced components (source: ARBURG GmbH + Co KG)

In general, the modern control technology of the production cell allows all production parameters of the injection-molding machine and also the parameters of externally connected measuring systems to be evaluated, saved and assigned to the individual components using modern data acquisition tools. This ensures seamless documentation and process-independent traceability.

Possible applications for direct fiber compounding
Thanks to its characteristics, fiber direct compounding offers the possibility of fine-tuning parameters such as fiber length and fiber quantity to the individual component properties and requirements. In addition, this process also allows the flexible use of different matrix materials. The range of applications in the automobile now includes not only components in the vehicle interior, such as seat shells and door modules, but also components in the engine.
area, such as housings, levers and joints. Taking a housing for the radiator as an example, the CO₂ footprint and energy requirements are considered in detail below.

**CO₂ and energy analysis: a case study**

In addition to cost considerations, the CO₂ footprint is an increasingly important factor in the selection of materials and processes. The total CO₂ balance of a plastic component depends on many parameters that are relevant during the production, use and disposal phases, each having very different proportions in the CO₂ balance. The energy requirements of plasticizing and mold temperature control as well as the compressed air and electricity requirements of the system technology used play an important role in the CO₂ balance of the production phase. The influence of the FDC process on the CO₂ balance of the production phase is considered in more detail below.

![Fiber-reinforced housing component for use in the automobile](source: ARBURG GmbH + Co KG)

The two methods for producing a housing installed in the vehicle engine compartment are compared below. In the first method, the housing is produced in polypropylene (PP), which is fiber-reinforced by means of direct fiber compounding. In the second process, the component is made from PP long glass fiber granulate. The investigations show that the FDC process achieves a CO₂ reduction of approx. 5 - 10% compared to the long glass fiber granulate, which is largely due to the compounding and pelletizing process not being required (see Diagram 3).
The matrix material used has a very great influence on the CO₂ balance of a component. The production of polyamide granulate thus has a CO₂ footprint of approx. 9 kg CO₂/kg. In contrast, the production of polypropylene only creates approx. 2 kg CO₂/kg in the production phase (see Diagram 5). If the entire CO₂ footprint of the housing component is now considered, the type and quantity of the matrix material used require the largest proportion of the energy required. This means that selection of the material is of enormous importance, since it has the greatest impact on the overall CO₂ balance (see Diagram 4). In addition to the significant reduction in emissions, the procurement costs for polypropylene are significantly lower than for polyamide. Both factors are of decisive importance in the component design and in material selection and must already be taken into account in this phase.
In the housing example the change from PA with short glass fibers to PP LGF reduces emissions by around 75% in the production phase. Additional potential savings result from the high global availability of polypropylene and the situation-related use of recycled matrix or fiber materials. These possible additional savings have not however been quantified for this particular application example. There is an additional CO$_2$ reduction during the utilization phase due to polypropylene having a lower specific weight than polyamide.
Diagram 5: Emissions during the production of various plastics (source: K-PROFI)

In summary, in the example described the substitution of polypropylene for polyamide in combination with the FDC process provides great advantages in terms of cost-effectiveness, as well as material and component properties. In addition, fiber direct compounding also enables component developers to improve the CO$_2$ footprint of production processes by using 'simple standard materials'.

**Summary**

In summary, the advantages of the method presented are:

1. Improved cost efficiency
2. Greater flexibility (materials / fibers / proportions)
3. Less dependence on material suppliers
4. Shorter transportation routes
5. Improved CO$_2$ balance

The FDC process is already being used successfully in high-volume series production. These FDC-optimized components meet or improve all quality requirements at significantly lower costs. The production processes can be fully automated and can be quickly integrated into the particular production environment thanks to networked control technology.

**Outlook**

The major trends in the automotive industry are electromobility, autonomous driving and, in recent years, requirements regarding resource efficiency and sustainability that have become increasingly important. In order to fulfill the latter and also to achieve the greatest possible
range, especially in electric automobiles, the use of fiber-reinforced plastics represents a good option. However, it is already possible in the design and production phases to probe energy and resource-saving processes and to consider the choice of materials with regard to their CO₂ balance (Table 5). This makes the planning and design phase even more important at the beginning. In the later production phase, these efforts pay off in the form of thrifty and cost-effective processes. The FDC process combines modular technology with flexible and simple options for process control. On the one hand, this enables easy integration into existing production processes and, on the other hand, a high level of flexibility, which is becoming more and more important in increasingly demanding and at the same time more volatile markets. The flexibility of the FDC process also enables it to be combined with other methods of plastics processing.